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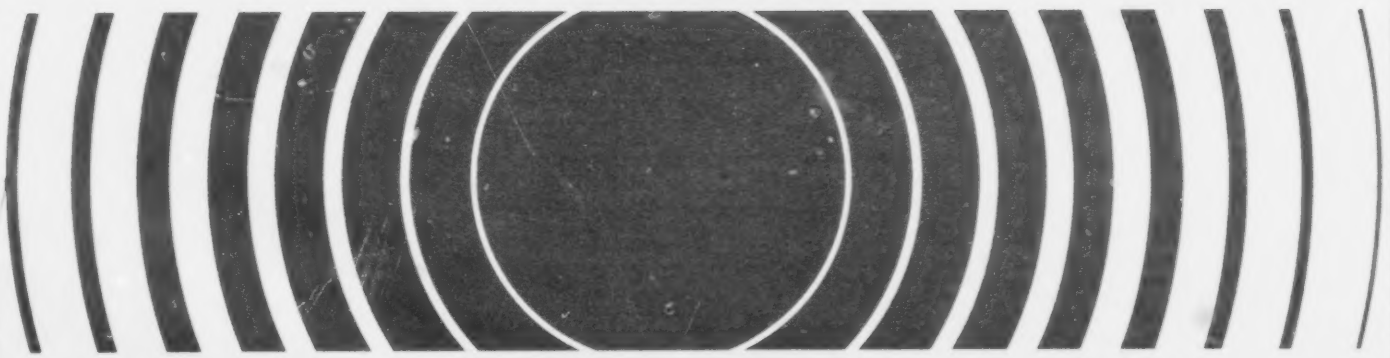

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Effect of Nuclear Power Generation on Water Quality in the Great Lakes

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ABSTRACT

The 1972 Great Lakes Water Quality Agreement between the United States and Canada concerning improvement of the water quality of the Great Lakes has led to a study of the probable effects of nuclear power generation on radioactivity levels in the lakes. From an environmental viewpoint, it is the long-term behavior of the effluents as they are discharged, mixed, and transported through the Great Lakes chain which is of primary interest. A simplified physical model of the Great Lakes system has been employed which assumes thorough annual mixing but allows for the perturbations in dilution volume required by the periodic establishment of thermoclines. Corrections are made, where necessary, for removal of radionuclides by sedimentation and equilibration. The results are given in terms of the concentration of radionuclides in each lake and the dose rates resulting from continuous, long-term ingestion of system waters.

Dose calculations are performed using equations promulgated by the International Commission on Radiological Protection in ICRP Report #10. Using the model described, it is possible to obtain analytical solutions for the coupled differential equations describing these quantities. In practice, a FORTRAN computer program, GLA-1, described in Annex III has been employed to reduce calculational effort.

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INTRODUCTION

The importance of the Great Lakes System to both the United States and Canada, along with the necessity for cooperation between the two countries in its management, has been recognized formally since signing of the "Boundary Waters Treaty" of 1909. This initial Treaty defined the extent of the "boundary waters," established the International Joint Commission of the United States and Canada and set forth the Commission's jurisdiction and authority.

This original Treaty was amplified and reinforced by a subsequent Agreement, Between the United States and Canada, on Great Lakes Water Quality which was signed in 1972. The new Agreement was specifically concerned "about the grave deterioration of water quality" in the lakes and its major thrust was "to restore and enhance water quality in the Great Lakes System." In addition, general and specific "water quality objectives" were set forth. The specific objectives were elaborated upon in Annex 1 of the Agreement where several caveats concerning radioactivity were introduced. The initial guideline was that "Radioactivity should be kept at the lowest practicable levels and in any event should be controlled to the extent necessary to prevent harmful effects on health." Furthermore, a procedure was established for developing a "refined objective ... for radioactivity (which would) be considered in the light of the recommendations of the International Commission on Radiation Protection." Upon receipt of this refined radioactivity objective, the International Joint Commission is to recommend new or modified specific water quality

objectives and, with the concurrence of both Governments, these shall be incorporated into the Agreement.

As a consequence of the Agreement, an international working group was formed to consider a refined radioactivity objective for the Great Lakes. Co-chairmen were from the United States Environmental Protection Agency and the Canadian Department of National Health and Welfare. In September of 1975 a draft of a "Refined Radioactivity Objective" was agreed upon by the working group, consisting of members representing National, Provincial, and State governments, and forwarded to the respective governments for their consideration. The U.S. State Department published this Objective for comment on April 5, 1977, 42 F.R. 18171. The proposed objective is reproduced in Annex I.

PURPOSE AND SCOPE

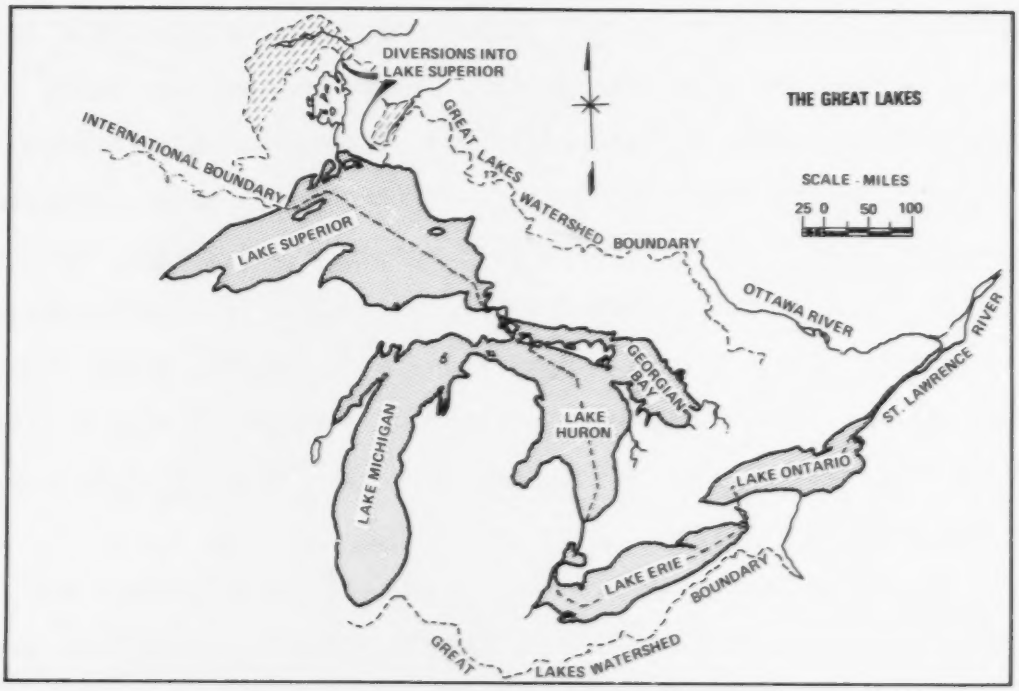
This paper describes a physical-mathematical model of the Great Lakes system that can be used to obtain estimates of the doses resulting from continuous ingestion of system waters as the concentrations of radioactivity in the various lakes change as a function of time.

The model can be used to consider various source terms: fallout from nuclear weapons tests, liquid effluents from nuclear power stations, and liquid and aerial releases from nuclear fuel reprocessing plants. Present radioactivity levels, due principally to fallout, are relatively well known and, in the absence of further atmospheric tests, should continue to decline. It is, therefore, the change in radioactivity levels due to projected U.S. and Canadian nuclear power generation in the Great Lakes basin which is of prime

concern. From an environmental viewpoint, it is the long-term effects which are of most consequence and the material presented in this report has concentrated on changes expected to occur over the course of many years rather than on detailed descriptions of localized phenomena which are seasonally variable in nature.

HISTORY AND TOPOLOGY

FIGURE 1



The Great Lakes basin, Figure 1, comprising the lakes and their tributary land areas, represents one of the major natural resources of both the United States and Canada. The international boundary passes through all lakes but Michigan, which lies wholly within the United States. Total area of the basin is about a half-million square miles which includes nearly a hundred thousand square miles of water

surface. Figure I shows the geographical details of the area lying within the Great Lakes drainage basin. This is one of the most highly industrialized areas in the nation and a significant recreational asset for the more than thirty million population presently residing in the basin. In addition, some activities, such as commercial fishing, depend directly on the water quality of the system. About sixty percent of the basin area lies in the United States with the balance in Canada. While the Canadian portion of the lakes lies wholly within one province; Ontario, seven States; New York, Pennsylvania, Ohio, Indiana, Illinois, Wisconsin and Michigan have boundaries which touch one or more of the Great Lakes. Downstream of the lakes, the St. Lawrence River forms, for a distance, the boundary between New York and Quebec. The final outflow to the Atlantic Ocean is entirely within Canada. Many large metropolitan areas (about 240 municipalities) situated on the lakes or connecting rivers use water of the Great Lakes for all or part of their drinking water supply as do various industries.

The Great Lakes are part of a chain of inland waterways. The outlet rivers serving the lakes, the St. Mary's, connecting Lakes Superior and Huron, the St. Clair-Detroit, flowing from Lake Huron to Lake Erie, and the Niagra, from Lake Erie to Lake Ontario, along with the Straits of Mackinac, lying between Michigan and Huron, allow entrained material from all upstream lakes to flow to the lower lakes. The only two lakes not interconnected are Michigan and Superior, both of which empty into Lake Huron. The character of the individual lakes differs considerably due to differences in usage, position in the

chain, and particularly depth and surface area. Many investigators[1,2] have compiled data on the Great Lakes.

In Table 1, published estimates of some of the pertinent physical characteristics of the lakes are compared. One of the controlling features of each lake is the "residence time" of the water contained in the lake - one of the major factors in determining the turnover of material suspended and dissolved in lake waters. In the simplest approximation, this residence time may be taken as the ratio of volume to outflow of the lake. Values of this quantity for each lake are included in Table 1, taken from reference (2).

Table 1

Physical Parameters of the Great Lakes[2]

Name of Lake	Volume V 10^{12} m^3	Surface Area a 10^{10} m^2	Mean Depth h Meters	Outflow Rate q 10^{11} m^3/yr	Water Residence (τ) Years
Superior	12.221	8.237	148	0.652	187
Michigan	4.871	5.802	84	1.582	31
Huron	4.6	5.951	77	1.573	29
Erie	0.458	2.567	18	1.752	2.6
Ontario	6.636	1.968	83	2.091	7.8

The basic character of the lakes changes drastically as one moves down the chain. Lake Superior, the largest body of fresh water in the world, is also one of the cleanest of the Lakes and is still regarded as oligotrophic. The flow of clean, cold water from Superior into

Huron tends to improve the quality of water in Lake Huron. Lake Michigan, which is really a large bay on the west side of the chain, is much more highly industrialized and, consequently, suffers from a larger degree of pollution. Under certain wind conditions the flow between Michigan and Huron may be reversed - in effect, backflushing from Huron to Michigan.

Huron, whose industrialization is concentrated at the southern end, where it drains into Erie, is helped by the large flow of clean water from Lake Superior. The general water quality of the lakes chain deteriorates markedly in the two lower lakes, Erie and Ontario. Most of the industrialization in the basin is centered in this area. For several reasons, pollution problems are worst in Lake Erie. Erie is the oldest and shallowest of the lakes but supports nearly half of the entire population of the basin. The amount of pollutants released into the small volume of Erie results in its being classified somewhere between mesotrophic and eutrophic. One interesting observation regarding Erie is that, although it contains only about two percent of the volume of the lakes, it produces over fifty percent of the total biomass in the Great Lakes and is also the largest supplier of seafood. The lowest of the Lakes, Ontario, receives the outflow from all upper lakes but its water quality is improved by several factors: the greater depth and larger volume of the lake allow it to absorb more pollution with less effect and Niagra Falls, with its large difference in elevation, acts as an aerator for the water leaving Lake Erie.

The hydrology of the Lakes is quite complicated. Michigan, for example, may be regarded as three lakes: Green Bay and a northern and southern portion split by an underwater ridge. All three have separate water circulation patterns which may increase the estimated residence time of water in the southern basin, over the estimate given in Table 1 for the Lake as a whole. Current patterns on the other lakes are similarly complicated. The north-south lakes, Michigan and Huron have wave actions which differ markedly from that of the remaining east-west lakes. The situation is further complicated by thermal stratification of the lakes during the warmer months of each year. The depth of the dividing line between the warmer upper layer, the epilimnion, and the colder portion, the hypolimnion, differs only slightly for each lake. In the deeper lakes, Superior and Huron, it is about 20-25 meters deep and in Ontario about 15-20 meters while for Erie it approaches the bottom over most of the lake. However, the complicated current action and seasonal breakup of the thermocline tend, on an annual scale, to insure thorough mixing of the lakes.

PHYSICAL MODEL

1. Radionuclide Concentrations

From the foregoing discussion, it is obvious that a detailed analytical treatment embodying all geographical and hydrological features of the Great Lakes would be extremely complex. However, the use of realistic simplifying assumptions results in a much more tractable analysis. The major assumptions are:

1. That the lakes comprise a set of five bodies of water characterized by constant total volume, constant outflow and inflow,

and constant surface area. Since all these quantities are based on averages, these assumptions are reasonable.

2, That each lake, on the time scale of interest here (decades), is perfectly mixed. For the reasons discussed in the previous section, this assumption is expected to be nearly exact.

3. That the thermocline exists for one-half of each year at a constant depth of 17 meters (50 feet) in each lake. All inflow and outflow during this period is from the epilimnion only. While this assumption overestimates the period of existence of the thermocline, it has little effect on the long-term lake concentration - since perfect mixing is assumed at the end of each year - but is slightly conservative in that drinking water is drawn from the epilimnion, which has a higher nuclide concentration, during this period.

For this model, the relatively simple governing equation is

$$V_i \frac{dC_i(t)}{dt} = R_i - \lambda_r C_i(t) - \lambda_p C_i(t) - q_i C_i(t) + \sum_{j<i} q_j C_j(t) \qquad (1)$$

where

C_i = concentration for ith lake [Ci/Cm^3]

R_i = input rate into ith lake [Ci/y]

V_i = mixing volume of ith lake [Cm^3]

λ_r = radioactive decay constant for this nuclide [y^{-1}]

λ_p = decay constant for physical removal (sedimentation, etc) [y^{-1}]

q_i = volumetric flow out of ith lake [Cm^3/y]

Because of the summation over j, a major difficulty in solving the equation arises in that each C_j term embodies the complete differential equation for all preceeding lakes, thus complicating the analytical expressions for the lower lakes.

We have chosen to apply the Laplace transform in order to obtain solutions to these equations. The transformed equation for C, using s as the transform variable, is

$$C_i(s) = \frac{R_i}{V_i}\left[\frac{1}{s(s + k_i)}\right] + \frac{C_i^o}{(s + k_i)} + \sum_{j<i} \frac{q_j C_j(s)}{V_i(s + k_i)} \qquad (2)$$

where $k = (\lambda_r + \lambda_p + \frac{q_i}{V_i})$ depends on both the characteristics of the lake and the physical properties of the radionuclide. C_i^o is the initial lake concentration. For Lakes Superior and Michigan, which are assumed to have no tributaries, the C_i^o term vanishes and the equation reduces to

$$C_i(s) = \frac{R_i}{V_i}\left[\frac{1}{s(s + k_i)}\right] + \frac{C_i^o}{(s + k_i)} \qquad (3)$$

Although equation (3) is relatively uncomplicated, the general equation (2) becomes increasingly more complex as we proceed down the chain of lakes. The transformed solutions to these general equations comprise only terms of the form

$$C(s) = \frac{f(s)}{g(s)} \qquad (4)$$

in which f(s) is constant and g(s) is the product of linear, non-repeated factors $g(s) = (s+k_1)\ (s+k_2)\ldots(s+k_n)$.

To reduce the effort required in solving such expressions, a variation of Heaviside's partial fraction expansion[3], is applied.

$$\mathcal{L}^{-1}\left\{\frac{1}{g(s)}\right\} = \sum_{n=1}^{m} \frac{1}{g(k_n)}\ e^{-k_n t} \qquad (5)$$

Using (5), the solution to equation (3) is

$$C_i(t) = \frac{R_i}{V_i}\left[\frac{1}{k_i} - \frac{1}{k_i}\ e^{-k_i t}\right] + C_i^o\ e^{-k_i t} \qquad (6)$$

For the next Lake, equation (2) includes expressions for the preceeding Lakes.

$$C_i(s) = \frac{R_i}{V_i}\left[\frac{1}{s(s+k_i)}\right] + \frac{C_i^o}{(s+k_i)} + \sum_{j<i}\frac{q_j}{V_i}\ \frac{1}{(s+k_i)} \left\{\frac{R_i}{V_j}\left[\frac{1}{s(s+k_j)}\right] + \frac{C_j^o}{(s+k_j)}\right\} \qquad (7)$$

where the summation over j indicates the presence of two terms, one for Lake Superior and the other for Lake Michigan, the C(s) terms for the lakes corresponding to the C_j(s) terms in equation (2).

It is evident that as the differential equation for each lake in the progression is transformed, each term will contain an additional

factor $(s + k)^{-1}$. Again, solutions may be found using inverse transforms.

2. The Time Dependence of the Dose to Reference Man

The concentrations of radioactivity, calculated as shown above, can be used to find the annual dose rate and cumulative dose to reference man due to ingestion. Because the radioactivity in the lakes may be a strongly varying function of time, due to the projected growth of nuclear power, dose estimates cannot be based on a constant intake of activity over the time necessary to reach equilibirum in the body except for nuclides having a relatively short effective half-life. In order to illustrate their time dependence, the dose rate and dose calculations presented here are based on equations and data presented in ICRP 10[5] and ICRP 10A[6]. This dose is different from the committed dose equivalent from one year's intake considered in the proposed objective which is defined in terms of the TED 50, the Total Equivalent Dose to ICRP Reference Man integrated over 50 years, Annex I. Methods for calculating the TED 50 are outlined in Annex II.

The ICRP equations for organ burden, b(t), and cumulated activity, B(T), have been revised slightly to conform to program usage. Both dose and dose rate are predicated, at present, solely on the assumed consumption by reference man of 2.2 liters of drinking water per day. This quantity is larger than usual to account for the contribution from food pathways.

Over a time interval short enough to treat the average concentration as constant, the intake, I(t), is directly proportional

to the concentration. Integration of the ICRP equations for organ burden and cumulated activity are straightforward if the retention function, R(t), contains only exponential terms. For the isotopes of interest here retention functions of this form are given in reference 5. For ingestion at a constant average intake, I,

$$b(t) = \bar{I} \int_o^t R(t - \tau)d\tau \qquad (8)$$

and

$$B(T) = \int_o^T \int_o^t R(t - \tau)d\tau dt \qquad (9)$$

Since the retention function, R(t), is the sum of a series of exponentials,

$$R(t) = \sum_{n=1} \alpha_n e^{-\beta_n t} \qquad (10)$$

where α and β are constants and each term in the integral defining the organ burden will be of the form

$$b(t) = \bar{I} \int_o^t \alpha_n e^{-\beta_n (t - \tau)} d\tau \qquad (11)$$

There are two solutions for this equation. The first yields the organ burden

$$b(t) = \frac{\alpha_n \bar{I}}{\beta_n} \left[1 - e^{-\beta_n (t - t_1)} \right] \qquad (12)$$

at any time during the period, beginning at time t_1, of ingestion. The second solution gives the organ burden

$$b(t) = \frac{\alpha_n \bar{I}}{\beta_n} \left[e^{-\beta_n (t - t_2)} - e^{-\beta_n (t - t_1)} \right] \qquad (13)$$

at any time subsequent to t_2, the end of the ingestion period. The dose rate depends only on the organ content at some time t. However, cumulated activity depends on the whole time history of ingestion so that the sum of equations (12) and (13) must be used in evaluation of the total dose over a period T. T may correspond to the 50-year ICRP occupational exposure although longer periods are more applicable to the general population. The cumulated activity is then

$$B(T) = \frac{\alpha_n \bar{I}}{\beta_n} \left\{ \int_{T_1}^{T_2} \left[1 - e^{-\beta_n (t - t_1)} \right] dt + \int_{T_2}^{T} \left[e^{-\beta_n (t - t_2)} - e^{-\beta_n (t - t_1)} \right] dt \right\} \qquad (14)$$

where T_1, T_2, and T are analogous to the t values used in the organ burden equations. Performing the integration and collecting terms,

$$B(T) = \frac{\alpha_n \bar{I}}{\beta_n} \left\{ (T_2 - T_1) + \frac{1}{\beta_n} \left[e^{-\beta_n (T - T_1)} - e^{-\beta_n (T - T_2)} \right] \right\} \qquad (15)$$

3. Computer Program

These solutions have been incorporated into a FORTRAN IV computer program to facilitate parametric studies. Individual lake solutions are functions of time, lake and nuclide. The time dependence is usually solved for in annual increments and, to account for the existence of a thermocline, the first half year uses the total lake volume as the mixing volume while the last half year presumes a 17 meter depth for the thermocline and uses the product of this depth and the lake surface area as the mixing volume. Lake outflows remain constant in the epilimnion, with equilibration dependent on the concentration above the thermocline, but nuclides in the hypolimnion are removed only by radioactive decay. Where applicable, sedimentation losses are also considered.

Several options are available for specification of the source terms. Detailed assumptions regarding reactor types are required since the liquid discharges from each differ significantly. These releases also depend greatly on the degree of sophistication of the liquid radwaste system employed by each type of reactor. Since a detailed examination of the radwaste system for each operating reactor would be prohibitively time consuming and is not possible for plants scheduled for future operation, it has been necessary to make some assumption regarding these releases. To this end, we have utilized the results of an in-depth environmental analysis[7] which presented typical releases expected from four classes of both BWR and PWR liquid waste system representing a range of treatment from minimum to maximum. This data is incorporated into the computer program for use

as a source option. Thus, the simplest option consists of reading in the number of BWRs and PWRs (nominal 1000 mWe) on each lake along with the radwaste system type and allowing the program to internally generate source terms for each lake and isotope. Alternatively, the actual source terms for each lake and isotope may be directly entered or the two options may be combined.

Basically the program determines the concentration at the end of the first half period, using the actual lake volumes, and then the concentration at the end of the last half period, using the 17 meter depth mixing volume. The dose rates are determined for each half period using linear averages of the respective concentrations. To begin the next time period, the concentrations in both parts of the lake are combined, to represent dissolution of the thermocline, and obtain an average lake concentration, $\overline{C}$.

$$\overline{C} = C_{17m}V_{17m} + C_h(V_t - V_{17m})/V_t \qquad (16)$$

This average concentration is then converted to dose rates and doses, using equations (8) and (9), in the following manner:

Based on a consumption rate of 2.2 liters per day and a 365.25 day year, the intake, I, is

$$\overline{I} = 8.04 \times 10^5 \, \overline{C} \left[\frac{C_i}{y}\right] \qquad (17)$$

where C is the average nuclide concentration. From equation (1) of reference 5, the dose rate and total dose are directly related to the time integrals of radioactivity by the factor,

$$\frac{3.2 \times 10^9 \ dis}{d \ \mu Ci} \quad \frac{1.6 \times 10^{-6} \ erg}{MeV} \quad \frac{gm \ rad}{10^2 \ ergs} \quad \frac{\frac{Mev}{dis}}{rad/rem} \quad \frac{1}{m \ gms} \quad \frac{365.25d}{y}$$

$$\frac{10^6 \ \mu Ci}{Ci} = 1.87 \times 10^{10} \ \frac{\varepsilon}{m} \quad \frac{rem}{Ci\text{-}y} \qquad (18)$$

and the dose rate for an interval having average annual concentration C, is

$$\dot{D}(t) = (1.87 \times 10^{10} \frac{\varepsilon}{m}) (8.04 \times 10^{5}) \overline{C} \int_{o}^{t} R(t - \tau) d\tau \left[\frac{rem}{y}\right] \qquad (19)$$

with the total dose, over the residence time, T, of the nuclide in the organ given by

$$D(T) = (1.87 \times 10^{10} \frac{\varepsilon}{m}) (8.04 \times 10^{5}) \overline{C} \int_{o}^{T} \int_{o}^{t} R(t - \tau) d\tau dt \ [rem] \qquad (20)$$

In order to present results which are compatible with present usage as regards dose rates and doses, these quantities were calculated using the methods and definitions of references 4, 5, and 6. These dose rates and doses were calculated using the ICRP equations:

$$\dot{D}(t) = 51.2 \ \frac{\varepsilon}{m} \ b \ (t)$$

and

$$D(t) = 51.2 \ \frac{\varepsilon}{m} \ B \ (t)$$

Values for ϵ, the average energy absorbed per disintegration, and m, the critical organ mass, are taken from Table 1 in reference 5.

The data required to obtain solutions for five isotopes (H^3, Co^{60}, Sr^{90}, Cs^{134}, Cs^{137}) are presently stored in the program but other radionuclides may easily be added. At present, this data includes correction factors, in the form of the effective decay constants indicated in equation (2), to account for equilibration of

tritium[8] and sedimentation of cesium[9]. A listing of the computer program, along with the input instructions is contained in Annex III.

The standard output consists, for each isotope, of the average radionuclide concentrations for each year and Great Lake. A summary table giving annual dose rates and cumulative doses by year for each lake is also printed out. The critical organ assumed for each isotope is printed out at the head of each column.

PROBLEM DESCRIPTION

The purpose of the analysis is to estimate the effect on the Great Lakes basin of nuclear power plant operation through the year 2050. To accomplish this it is necessary to consider both U.S. and Canadian stations. Separate solutions were obtained for each of these sources, described below, in order to compare the relative effects of each.

Sources

A. U.S. Light Water Nuclear Power Stations

That portion of the total liquid effluent source discharged by nuclear power plants is treated in two time steps. In the first, beginning in 1962, when the first reactor located on the Great Lakes began operation, and running until 1980, the actual type (BWR, PWR) and location, by lake, is used based on a compilation[10] issued by the AEC. Known reschedulings and cancellations have been incorporated into this list.

For the time period after 1980, the number of nuclear power stations is based on a an ERDA study[11] projecting nuclear power growth through the year 2000. In view of recent events this projection is

likely to be too high, see Annex II. Since the study is not specific as to type or location of plant, these were estimated in the following manner: The number of reactors sited on the lakes was taken to be in the same ratio to the total number in a given year as the actual number (approximately 18 percent) in 1980 to the study total in that year. As the ERDA study values are given in five year increments, annual values were obtained by linear interpolation. Apportionment of reactors between the various lakes was assumed to be directly proportional to that planned for 1980. For reactor type, however, a national ratio of 2 PWR to 1 BWR has been postulated and this ratio has been assumed for this study. Since the actual 1980 PWR/BWR ratio deviates considerably from this average for individual lakes, this ratio has been approached by interchanging reactor types, where necessary, until the total generating capacity on each lake was sufficient to attain the 2:1 ratio without disturbing the actual 1980 distribution. In Table 2, the resulting incremental number of reactors of each type becoming operational is given by year.

TABLE 2

ANNUAL INCREMENTAL POWER (MWe)
GENERATION BY LAKE
($\times 10^{-3}$)

Starting Date	ΔP (BWR/PWR)			
	M	H	E	Ø
1962	.070/			
69				.625/.490
70	.497/			
72	/.700			
73	/2.09			
74	/3.17			.821/
75			/.906	
76			1.12/	
77	.660/			
78				1.80/
79		/.492	2.23/	
1980		/2.06	1.10/	
81	1.86 /.222	.740	/1.55	/.874
82	.690/1.39	.600/.130	/1.56	/.880
83	.700/1.38	.250/.500	/1.54	/.870
84	.690/1.40	.250/.490	/1.56	/.870
85	.690/1.38	.240/.490	/1.55	/.870
86	1.06 /2.11	.375/.750	.786/1.57	.445/.890
87	1.06 /2.11	.375/.750	.784/1.58	.445/.885
88	1.05 /2.11	.374/.748	.790/1.58	.440/.885
89	1.06 /2.11	.376/.752	.786/1.57	.444/.888
1990	1.05 /2.12	.370/.746	.784/1.58	.443/.886
91	1.34 /2.86	.480/.954	1.00/2.00	.563/1.12
92	1.34 /2.86	.470/.940	1.00/2.00	.560/1.12
93	1.33 /2.67	.480/.954	.990/1.99	.560/1.12
94	1.34 /2.67	.470/.940	1.00/2.00	.560/1.12
95	1.34 /2.68	.480/.950	.990/1.99	.560/1.13
96	1.55 /3.09	.470/.950	1.15/2.30	.650/1.30
97	1.55 /3.10	.548/1.10	1.15/2.31	.650/1.30
98	1.54 /3.09	.548/1.09	1.16/2.30	.650/1.30
99	1.55 /3.10	.548/1.10	1.15/2.31	.650/1.30
2000	1.55 /3.10	.548/1.10	1.16/2.31	.650/1.30

B. Canadian Heavy Water Reactor Power Stations

Source terms for these heavy water reactors were based on actual releases furnished by Canadian utility operators[12] for the Pickering Station. These releases were normalized for power level and Canadian estimates of projected nuclear plant construction used to obtain time dependent source terms. While the most significant effluent from these reactors is the tritium produced in the heavy water and subsequently evaporated, the remaining major effluents are also considered. The estimated future magnitude of these releases is believed to be high since there are cogent economic reasons for reducing such losses.

RESULTS

The program described has been run, using the standard options of the previous section, for the period 1962 to 2050. The nuclear power plant sources were determined by reading in the numbers of nominal 1000 MWe plants, in one year increments, and assuming, as per reference (7), system 2 radwaste effluents until 1978 and system 3 thereafter.

Results were obtained for the source terms described above using two sets of boundary conditions. In the first, it was assumed that all sources in the year 2000 remained in operation at a constant rate through the year 2050. In the second, it was assumed that all sources were shut down in the year 2000 so that the period from 2000 to 2050 reflects only the effects of radioactive decay and lake turnover.

Due to the large amount of information (i.e., results are lake, isotope, and time dependent) generated in each run, no attempt is made

to show every aspect of the two calculations outlined above. Rather, some representative graphs indicating typical behaviour are shown in Figures 2 and 3, respectively. These give the tritium concentrations for each lake and the dose rates in Lake Ontario, due to U.S. nuclear power generation, through the year 2050.

Table 2 shows the dose rates in the year 2050 for each lake due to both U.S. and Canadian reactors. It should be noted that these dose rates are based on continuous ingestion from the year of initial operation (1962) to the year indicated. The only operating reactors through the period 1962-1970 were on Lake Michigan. Sources in the remaining lakes during this period are due to flow from Michigan through connecting rivers. Subsequent to this period generating stations begin to come on line in the other lakes until, by 1980, operating reactors are projected for all lakes but Superior. None of the concentrations are significant until about 1980 after which there is a sharp rise through the year 2000.

Based on the model described in the text, by far the largest cumulative dose is due to the concentration of tritium in lake waters. The vast majority of the tritium present is due to the effluent from Canadian heavy water reactors. The remaining isotopes contribute far less to the total dose.

These results reflect ICRP methodology for calculating dose rates to reference organs, as exemplified in the references given above. As noted previously, the dose calculation and the organs considered will change when the new ICRP dose models are issued. The radionuclide

concentrations calculated by this program are used to calculate the 50 year dose commitments according to new ICRP methods in Annex II.

FIGURE 2
TRITIUM CONCENTRATION FROM U.S. POWER REACTORS

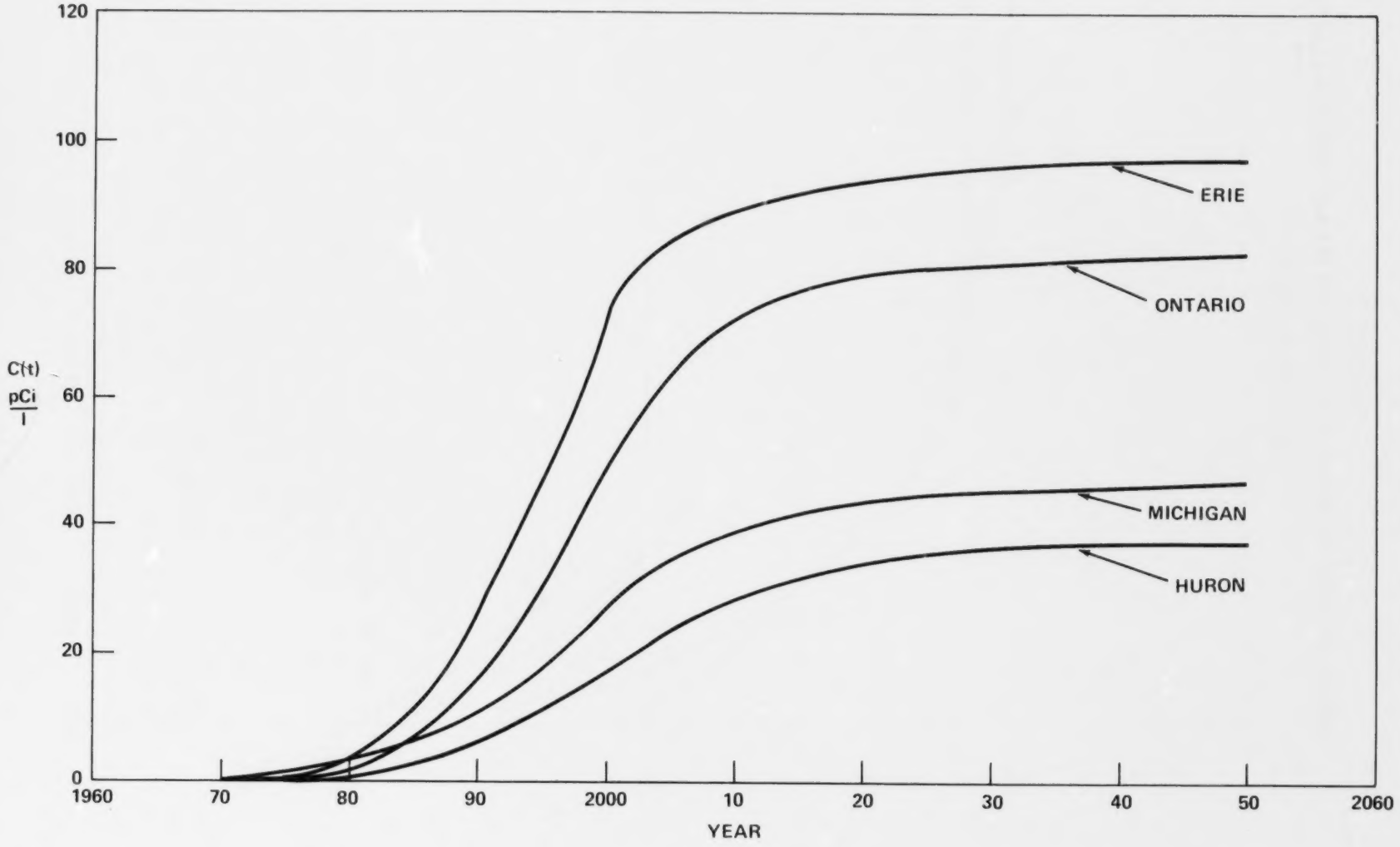
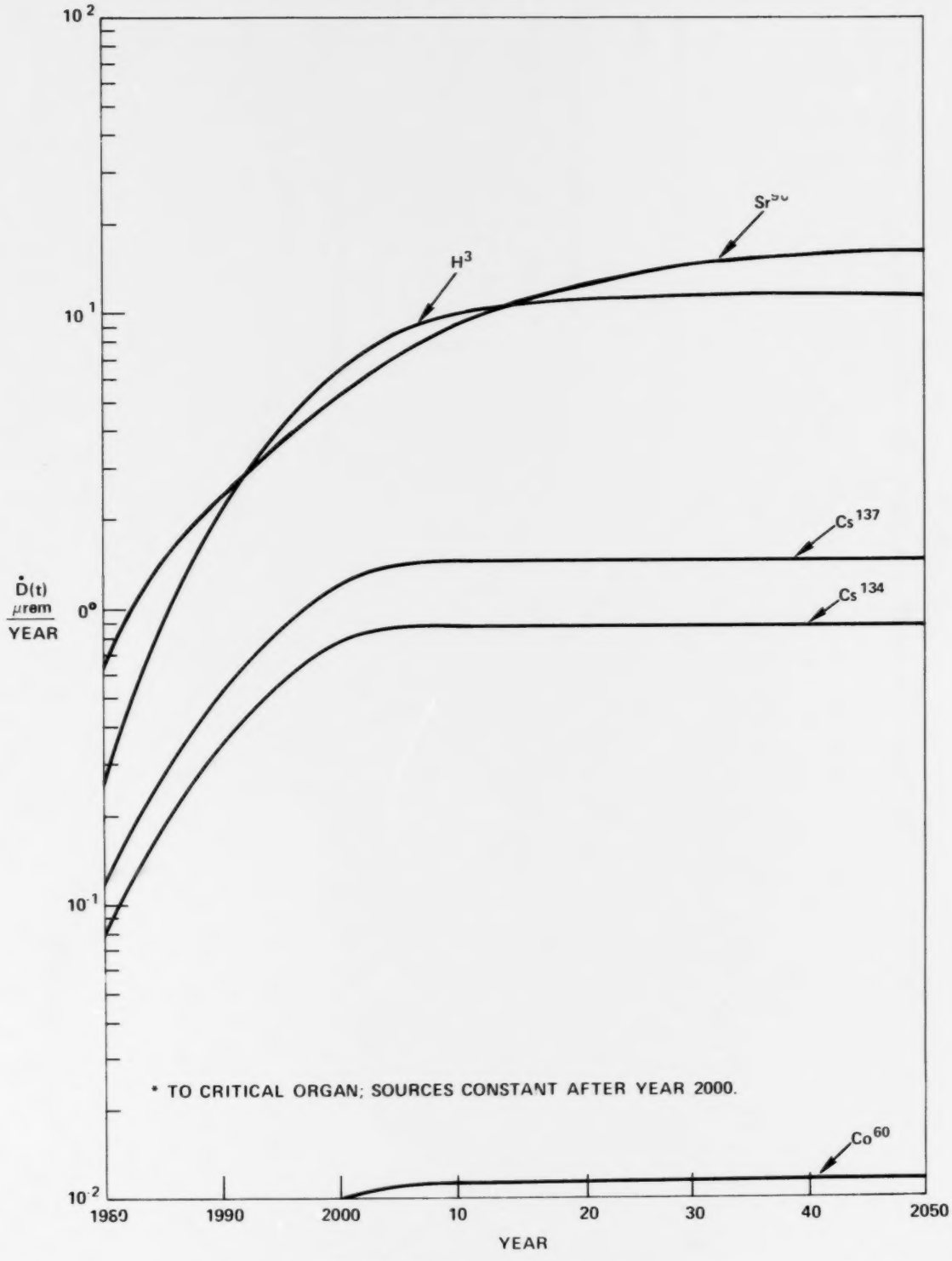


FIGURE 3

DOSE RATES* DUE TO U.S. POWER REACTOR EFFLUENTS

LAKE ONTARIO



DOSE RATES* DUE TO U.S. REACTOR EFFLUENTS

TABLE 2

DOSE EQUIVALENT RATE IN THE YEAR 2050*

(MICROREM/YEAR)

ISOTOPE AND CRITICAL ORGAN		LAKE MICHIGAN	LAKE HURON	LAKE ERIE	LAKE ONTARIO
TRITIUM (BODY WATER)	1	6.402	5.205	13.36	11.34
	2		137.8	97.91	257.7
COBALT-60 (TOTAL BODY)	1	0.007	0.004	0.017	0.012
	2		0.041	0.028	0.082
STRONTIUM-90 (BONE)	1	8.778	8.112	17.29	17.07
	2				
CESIUM-134 (TOTAL BODY)	1	0.635	0.283	2.097	0.874
	2		0.199	0.064	0.447
CESIUM-137 (TOTAL BODY)	1	0.995	0.478	2.842	1.452
	2		0.907	0.393	1.956

* SOURCES CONSTANT AFTER THE YEAR 2000.

1. U. S. NUCLEAR POWER REACTORS
2. CANADIAN POWER REACTORS

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4. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Permissible Dose for Internal Radiation, ICRP Publication 2, Pergammon Press, N.Y., N.Y. (1959).

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6. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. The Assessment of Internal Contamination Resulting from Recurrent or Prolonged Uptakes, ICRP Publication 10A, Pergamon Press, N.Y., N.Y. (1971)

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12. Personal Communication, K. Y. Wong, Supv., Central Health Physics Services, Ontario Hydroelectric, to A. H. Booth, Director, Radiation Protection Bureau, Department of Health and Welfare (Canada) dtd 11/26/74.

ANNEX I

Refined Radioactivity Objective

REFINED RADIOACTIVITY OBJECTIVE FOR THE GREAT LAKES WATER QUALITY AGREEMENT

SUMMARY

This document represents the joint recommendations of U.S. and Canadian advisory groups on a radioactivity objective to preserve the water quality of the Great Lakes. The objective is in terms of a dose equivalent to ICRP Reference Man from a standard annual intake of the Great Lakes water. The recommended objective for the general water quality in the Great Lakes is that level of radioactivity which results in a whole body dose equivalent not exceeding one millirem. Release of radioactive materials shall be as low as reasonably achievable and controlled by specific actions at defined levels.

The Canada-United States Great Lakes Water Quality Agreement specified radioactivity as a constituent of water for which there should be an agreed Water Quality Objective. The relevant statements in the Agreement are as follows:

Annex 1, Section 1(h) states: "Radioactivity should be kept to the lowest practicable level. In any event, discharge should be controlled to the extent necessary to prevent harmful effects on health."

Annex 1, Section 7(h) further states: "for radioactivity, the objectives shall be considered in the light of the recommendations of the International Commission on Radiation Protection."

Further, this section requires the parties to consult for the purpose of considering "refined objectives for radioactivity".

Subsequently, advisory groups were formed in Canada and in the United States to consider the technical aspects involved in developing such "refined objectives". The present report was developed following extensive consultation between the two groups.

To restore and enhance water quality in the Great Lakes System, as called for in the Agreement, it is necessary to limit the quantity of radioactive materials introduced due to activities of the United States of America and Canada. An acceptable quality for water in the system can best be maintained by a vigorous application of appropriate control measures. These controls should be applied to radioactive effluents from point sources as well as run-off, drainage, and seepage from non-point sources, including aerial deposition.

The Radioactivity Objective for the Great Lakes Basin is based principally on three criteria: (1) Introduction of radioactive materials into System Waters should be permitted only when it results from socially beneficial activities.

(2) The concentration of radioactivity in the System Waters and in biota should not constitute an unacceptable health risk on either a long-term or short-term basis.

(3) Since the ingestion of any amount of radioactivity may involve some risk, additional controls should be instituted until their cost is incommensurate with any further reduction in potential health risks.

In keeping with these criteria, several recommendations have been agreed to. These recommendations refer to an Ambient Water Quality Objective, the control of radioactive releases, a defined hierarchy of Action Levels and the surveillance of Lake Waters. None of the proposed levels, including particularly the lowest, should be interpreted as necessarily defining an acceptable dose to the population using System Waters. The acceptability of any dose level depends on whether the three criteria given above are being met in a responsible manner. It is further proposed that these objectives be reviewed at least every five years to consider any necessary changes and to determine if they continue to reflect "as low as reasonably achievable".

AMBIENT WATER QUALITY

It is necessary to specify an ambient water quality level for the Lakes as a whole so that contributions from all sources including aerial deposition are taken into account. This water quality level is expressed in terms of the total equivalent dose to ICRP Reference Man integrated over 50 years (TED). It is proposed that water quality outside of any Source Control Area, as defined herein, shall not result in a TED greater than one millirem to the whole body from daily ingestion of 2.2 liters of Lake water for one year. Therefore, even for lifetime (50 years) ingestion, the annual dose rate will not exceed 1 millirem per year. The total equivalent dose to a single organ or tissue shall be in proportion to the dose limit recommended by the ICRP for that tissue. Because levels in the lakes may fluctuate as a result of uncontrollable releases, such as fallout from weapon testing, it is further recommended that the one millirem value be reviewed at least every five years to ensure that the contribution from these uncontrollable releases does not constitute an unreasonable proportion of the dose.

CONTROL OF RELEASE OF RADIOACTIVE MATERIALS

Dumping of radioactive wastes or other radioactive material into waters of the Great Lakes system is prohibited. Dumping is defined as any deliberate disposal of packaged or unpackaged wastes or other matter from vessels, platforms or other man-made structures into the System Waters, but dumping does not include the release of effluents

that are permitted by the responsible regulatory bodies.

Both the concentration and quantities of radioactive materials released into the Great Lakes System shall be controlled to the extent necessary to protect public health and the environment. Releases of radioactive materials from each operation or type of operation should be controlled so as to conform with the ICRP recommendation that "all doses be kept as low as is reasonably achievable economic and social considerations being taken into account". (ICRP Pub. 22 1973).

Effluents should be controlled by the regulatory bodies having jurisdiction, taking into account the cost of further reductions, the efficacy of available additional control measures, and the significance of the potential reduction in public health risk associated with further discharge limitations.

A graded scale of actions for each identifiable source shall be implemented based on annual average measurements of the TED in water monitored at the periphery of each source control area, in accordance with the action conditions given below in Table I.

TABLE 1 - Action Conditions

Condition	Action Required	Action level TED_{50}(mrem)
A	Periodic confirmatory monitoring	Less than 1.
B	Source investigation and corrective action if releases are not as low as reasonably achievable.	Between 1 and 5.
C	Corrective action by responsible regulatory authorities.	In excess of 5.

Action levels are to be calculated in accordance with the dose models used by the ICRP.

The annual average shall be based on the average value of at least 4 measurements in a year. Since there is a relatively high probability of sampling error, measurements should be verified before action is taken.

When the concentrations of radionuclides in the water correspond to condition A, no corrective action is indicated. However, periodic monitoring is required to confirm that the condition does not change.

When the concentrations of radionuclides in the water correspond to Condition B, an investigation must be conducted to identify the source and the cause. If this investigation demonstrates that releases are as low as reasonably achievable no further action is necessary, otherwise, corrective action shall be taken.

Concentrations of radionuclides in the water corresponding to Condition C probably reflect a failure of effluent controls and are unacceptable on a continuing basis. The responsible regulatory authorities shall determine appropriate corrective actions to minimize the public health risk.

SURVEILLANCE

Adequate periodic monitoring of System Waters, sediment, and the appropriate food organisms contained therein should be provided for those radionuclides likely to be present in measurable concentrations. Such monitoring should be conducted under the direction of the responsible Federal, State, and Provincial jurisdictions and reported to the International Joint Commission. The nuclides and food organisms investigated, and sampling locations and frequency should take into account the known effluent sources and particular nuclides released.

The monitoring reports should include calculations of the TED_{50} to ICRP Reference Man from standard annual intake of the water since this is the parameter to be used in determining the applicable Action Condition. At present it is not necessary to determine explicitly the dose equivalents due to the intake of food harvested from the Lakes as they are relatively insignificant.

DEFINITIONS

1. Total Equivalent Dose (TED_{50}). For the purpose of this report, the total equivalent dose to a particular organ, tissue or the whole body is the cumulated dose equivalent over 50 years resulting from the daily ingestion of 2.2 liters of lake water for one year.

where:

$TED_{50} = \sum_i D_{50_i} Q_i N_i$ rem

D_{50_i} = total absorbed dose integrated over a period of 50 years after intake of the radionuclide "i".

Q_i = quality factor

N_i = product of all other modifying factors

ICRP report No. 10[1] lists the dosimetric data, including the TED_{50}, for a number of radionuclides.

2. Reference Man: For the purpose of this report, Reference Man refers to the definitions and parameters for adult males outlined in ICRP Report 23.[2]

3. Source Control Area: It is proposed that the "source control area" be defined as follows: "The source control area shall be bounded by a distance of 1 km radius from the point of release or, in those cases where the release point is to a narrow channel or river, the boundary shall be a point 1 km downstream from the source."

It is further proposed that the operator of a facility can request a larger source control area subject to the approval of the regulatory authorities and similarly these authorities may require a more restrictive area from an operator.

4. Ambient Water: The water in the Great Lakes System outside the source control areas.

(1) ICRP Pub. 10, 1968 Report of Committee IV, Pergamon Press.
(2) ICRP Pub. 23, 1975 Report of the Task Group on Reference Man, Pergamon Press.

ANNEX II

Impact Assessment of the Proposed Refined Objective for Radioactivity in the Great Lakes

Impact Assessment of the Proposed Refined Objective for Radioactivity in the Great Lakes

This assessment addresses two questions:

1. How do current levels of activity in the ambient water of the Great Lakes compare with the proposed objective?
2. In view of the anticipated increased discharges of radioactivity into Great Lakes water, how do future levels of radioactivity compare with the proposed objective?

Because the Refined Objective is part of an international agreement, the two parties agreed to use models for dose equivalents recommended by the International Commission on Radiation Protection (ICRP). The most recent ICRP recommendations were adopted in January 1977 (1) Some explanation of the new ICRP models is included below because many readers may be unfamiliar with recent ICRP concepts which are directly applicable to this assessment.

I. The Dosimetric Basis for Action Levels in the Objectives

In keeping with the new ICRP format, reference levels in the Refined Objective are in terms of the committed dose equivalent (1). In general, older methods of calculating dose based on the ingestion of a maximum permissible concentration of radioactivity, cannot be used to determine either dose commitments or compliance with the Refined Objective. Specific reference levels in the Objective are for a 50-year dose commitment (TED(50)), that is, the committed dose equivalent received over a 50-year period by an ICRP reference man consuming Lake water for one year at the daily rate of 2.2 liters per day.

The TED(50) reference levels specified numerically in the Refined Objective are for the total body. For cases where only a part of the body is exposed, dose commitments "in proportion to dose limits recommended by the ICRP," are applicable (Annex I). The new ICRP dose equivalents for single organ exposure are based on the risk relative to total body exposure, which is appreciably smaller. For example, the weighting factor for the dose to bone endosteum is 0.03; to red bone marrow 0.12 (1). Organ doses, i.e., the TED(50) due to the ingestion of Great Lakes water, must be multiplied by the appropriate ICRP weighting factor before a comparison is made to the numerical values in the Objective.

The Refined Objective establishes three action conditions (reference levels) based on the TED(50) due to the ingestion of Lake water at points beyond a source control area defined by the appropriate National authority. Action Condition A calls for "periodic confirmatory monitoring" when the TED(50) for whole body is less than one millirem. Action Condition B is a reference level requiring "source investigation and corrective action if releases are not as low as reasonably achievable" when the TED(50) (whole body) is between one and five millirem. If the annual average concentration of radioactivity in Lake waters is such that the 5 mrem TED(50) (whole body) is exceeded, Action Condition C requires "Corrective action by responsible regulatory authorities." It should be noted that compliance with these conditions are to be implemented by the National authorities in the U.S. or Canada legally responsible for the regulation of effluents. In the U.S. this would be the Nuclear

Regulatory Commission (NRC) for facilities licensed under the Atomic Energy Act.

From the discussion above, it is seen that it is not the purpose of the Objective to establish without exceptions a one millirem reference level for the Lakes. Rather, the Objective requires investigative action when this level is exceeded. Provided that regulated releases are as low as reasonably achievable, as currently required by both Federal Guidance and Regulations, a 5 mrem TED(50) (whole body) is within the numerical objective.

Because levels in the Lakes may fluctuate as a result of uncontrollable releases, such as fallout from weapon testing, it is further recommended in the Objective that the one millirem reference level be reviewed at least every five years to ensure that the contribution from these uncontrollable releases does not constitute an unreasonable proportion of the 50-year commitment dose.

II. TED(50) Due to Current Levels of Man-made Activity in the Lakes

Radioactivity in the Great Lakes is mainly a residual from nuclear weapons testing. In addition, nuclear facilities and naturally occurring radioactive material make small contributions to the total equivalent dose. Strontium-90, which entered as fallout from weapons debris, is the major contaminant. The reported range of current levels in the Lakes are as shown in Table 1.

Table 1

Strontium-90 in Ambient Waters of the Great Lakes (2,3)

Lake	Sr^{90} (pCi/l)	Date
Superior	0.5	1973
Michigan	0.8	1973
Huron	0.7	1976
Erie	1.0-1.1	1976
Ontario	0.8	1976

The data shown in Table 1 indicate that concentrations of Sr-90 are about 1 pCi per liter in ambient waters. Near the discharge areas of nuclear facilities, i.e, within the source control where the Refined Objectives do not apply, Strontium-90 levels may intermittently exceed this level. Tritium is also present in the Great Lakes due, again, to weapons testing. Current ambient levels of retention are in a range of 300 to 500 pCi/l. While these levels are much higher concentrations than for strontium-90, the dose commitment due to tritium ingestion is relatively small, Appendix A. Unlike the case for strontium-90 however, the concentration of tritium in some of the Lakes is expected to increase with time so that it becomes the more important pollutant, as discussed in Section III.

Dose Due to Current Levels of Strontium-90

As provided for in the Objectives, ICRP dose models are to be used to determine the TED(50) from the ingestion of Lake waters. Parameters in the new ICRP Committee II dose model for strontium-90 have been agreed on (4). These differ from older ICRP models, in that they are for the endosteal surface of bone and the red marrow of bone, not bulk bone as in the 1959 ICRP model (5) and are based on the retention functions for the alkaline earths given in ICRP #20 (6). Using these parameters the 50-year bone marrow dose due to ingestion of 1 pCi/l of Sr-90 at the rate of 2.2 liters per day for one year is 0.7 mrem; the TED(50) to endosteal surfaces is 1.2 mrem, Appendix A. These doses cannot be compared to the 1-5 mrem reference levels for total body exposure until weighted by appropriate ICRP estimates of risk following partial body exposure.

Relative to the risk following total body exposure, the sum of the risk to red bone marrow and endosteal bone due to current levels of strontium-90 in water (1 pCi/l) is 0.12 x 0.7 + 0.03 x 1.2 = 0.12 mrem. This sum is a factor of about eight less than Condition B in Refined Objectives and more than 40 times less than Condition C.

Due to radioactive decay and the gradual exchange of lake waters, the concentration of Sr-90 and tritium due to fallout occurring in the 1960's will decrease. By the year 2050 it is estimated that the concentration of strontium-90 due to this source (assuming no further fallout) will range from about 0.06 pCi/l (in Lake Superior) to 0.008 pCi/l (in Lake Michigan), compare with Table 1. By the year 2050, tritium concentrations due to fallout are expected to decrease to

about 3 pCi/l in Superior and 0.3 pCi/l in Michigan, the other Lakes having intermediate concentrations.

III. Future Levels of Activity in the Great Lakes Due to Planned Discharges

In 1975, EPA began a study in connection with the development of the Refined Objective to determine what influence present and planned nuclear facilities would have on the level of radioactivity in Great Lakes water.

Based on past and projected discharges into the Lakes, the concentration of strontium-90, tritium and other radionuclides in Lake waters has been calculated as a function of time taking into account the interchange of waters between Lakes in the Great Lakes chain, as described in the main report and in reference 7. Some of the results of these studies are reprinted in Appendix B.

Data on current plants, starting in 1962, and those scheduled to be liscensed were supplied by the NRC. Effluent releases from U.S. plants are discussed in Appendix B. Projections of the future number of U.S. nuclear power plants to be sited on the Lakes were taken from Curve D in the Energy Research and Development Administration (ERDA) study, "Nuclear Power Growth 1974-2000 (8)." In retrospect, this probably overestimated future impact since it led to a prediction that 193 gigawatts (electric) of U.S. nuclear power generation (about 200 reactors) would be sited near the Great Lakes by the year 2000. This is about two-thirds of the total U.S. nuclear power currently projected for year 2000 by Robert Fri, Acting Administrator of ERDA (9). It seems unlikely that such a large fraction of the nation's nuclear reactors will be sited on the Lakes.

Estimates of the projected growth in nuclear power plants bordering Canadian Great Lakes waters and estimates of their effluent discharges were provided by the Canadian representatives to the task group that prepared the Refined Objective. Canadian plans indicate that 50.6 gigawatts (electric) will be installed on Lakes Huron and Ontario by the year 2000. Since neither nation is currently planning nuclear facilities in the vicinity of Lake Superior, release of effluents into this Lake is not assumed in the EPA model. Again, this leads to an overestimate of the projected TED(50).

Based on the assumptions outlined above, estimates of the amount of U.S. and Canadian effluents discharged annually into the Lakes after the year 2000 are shown in Table 3.

Table 3

Projected Rate of Radioactive Effluents Entering the Great Lakes After the Year 2000

	Strontium-90 (curies per year)		Tritium (curies per year)	
Lake	U.S.	Canada	U.S.	Canada
Michigan	6.0×10^{-4}	-----	22,000	-----
Huron	3.8×10^{-4}	-----	7,400	387,000
Erie	1.6×10^{-3}	-----	15,600	-----
Ontario	1.3×10^{-3}	-----	8,800	460,000

It should be noted that almost all of the tritium released by Canadian heavy water reactors, which differ substantially from U.S. light water reactors, is discharged into the atmosphere. In estimating the amount

of Canadian effluents entering the Lakes, the Canadians assume that half of its tritium enters the adjacent Lake in the form of rainout. It is likely that this overestimates the actual impact of their releases on Lake Waters.

The EPA analysis indicates that except for tritium, effluents from power reactors are of little interest compared to either current levels due to fallout or the reference levels in the Objective. For example, the maximum strontium-90 concentrations due to power reactor discharges are expected to be less than 0.0016 pCi/l in the year 2000 and 0.0026 pCi/l in the year 2050, Appendix B. Compared to the current levels of strontium-90 in the Lakes (about 1 pCi/l) due to fallout, the amount that will be contributed by future nuclear power plants sited near the Lakes is negligible.

Urlike the case of strontium-90, the tritium concentration in the lower Lakes is expected to increase from current levels by the year 2050; in Ontario by a factor of about five, Appendix B. Most of this projected increase is due to the rainout of tritium from atmospheric releases in Canada. U.S. operations are expected to increase current levels of tritium by less than 20 percent.

Fifty-year dose commitments to the total body due to the discharges of tritium following the anticipated growth of nuclear electric power are shown in Tables 3A and 3B. Table 3A lists the TED(50) in the year 2000 after all of the projected plants have begun operation. Table 3B lists the $TED(50)$ in the year 2050; that is, after these (or similar plants) have been in full operation for 50 years. Dosimetric methods for tritium are outlined in Appendix A.

Table 3A

TED(50) Whole Body Doses Due to Tritium from Power Reactors in the Great Lakes through the Year 2000

Lake	TED(50) millirem
Michigan	0.002
Huron	0.05
Erie	0.04
Ontario	0.10

Table 3B

TED(50) Whole Body Doses Due to Tritium from Power Reactors in the Great Lakes Assuming 244,000 Megawatt Electric Generation Per Year Through the Year 2050

Lake	TED(50) millirem
Michigan	0.002
Huron	0.06
Erie	0.05
Ontario	0.12

Even though increased levels of tritium on the Great Lakes are anticipated, the TED(50) due to one year's ingestion of Lake waters is expected to remain a factor of eight or so below the lowest reference level in the Objective. It is seen by comparing Tables 3A and 3B that continued operation of the projected facilities for a 50-year period causes only a modest increase in the TED(50), about 20%. Operations leading to the effluent discharges shown in Table 3 for an indefinite

period after the year 2050 would not lead a tritium concentration that exceeds reference level A in the Refined Objective.

It should be noted that these projections are based on levels of effluent release that are the result of regulations previously imposed by the respective national regulatory authorities. Such existing U.S. regulations have been found to be as low as reasonably achievable (ALARA) taking economic and social costs into consideration (10).

IV. Dose Due to Current Levels of Radium-226

Radium-226, a naturally occurring alpha particle emitter is ubiquitous in the environment. However, it is seldom found in surface waters at any appreciable concentration. Heretofore, unusually high concentrations of radium in surface waters have been traced to man's disturbance of the natural environment.

Uranium mining is a good example. In the 1960's it was shown that the concentration of radium-226 in the Colorado River was increasing and that this increase was due to the mining, storage and treatment of uranium ores. Subsequently, levels in the Colorado River have dropped as the installation of effluent controls has become commonplace. A similar situation appears to have developed in Canada where uranium mining operations have resulted in contamination of the Serpent River which empties into Georgian Bay on Lake Huron. Table 4 lists measured concentrations of radium-226 in the Serpent River as a function of time. Clearly, the situation is coming under control. More recent Canadian data indicate an average annual concentration of 5.3 pCi/l (2).

Table 4

Annual Summaries of the Current Status of Radium-226 in Serpent Harbour, North Channel, Georgian Bay, Lake Huron, Lake Ontario(3)

Year	pCi/l
1966	11.7
1967	8.8
1968	8.8
1969	7.3
1970	8.7
1971	6.5
1972	5.7
1973	6.1
1974	5.5
1975	5.4

Nevertheless, Canadian environmental authorities appreciate the fact that these effluents result in 50-year dose commitments to bone that exceed action Condition P in the Refined Objectives and that remedial actions may be required (2). Similarly, in the town of Port Hope in Ontario, the processing of radium bearing ores has resulted in the localized contamination of near shore waters, via runoff from contaminated land. The most heavily impacted area has been the harbor of Port Hope. Recent monitoring data for this harbor show Radium-226 concentrations ranging from 1 to 2 pCi/l (2). Concentrations in the Port Hope water supply have remained below 1 pCi/l (2,3). Even though

Action Condition A has probably not been exceeded, clean up of source areas for radium contaminated runoff near Port Hope is in progress.

The conditions outlined above are exceptional and are not indicative of the Lakes as a whole. Unfortunately, radium concentrations apart from contaminated areas are so low that little effort has been made to routinely monitor for radium-226.[1] Instead, gross alpha particle activity is measured to establish an upper bound on the radium concentration.

Radium-226 has been specifically measured in at least three of the Lakes with the results shown in Table 5. For the purposes of this study 0.03 pCi/l is used as an estimate of the concentration of radium-226 in ambient Lake waters. Additional monitoring is needed to verify this estimate and it is used here as an interim value. However, the data are sufficient to indicate that the relatively high levels found in the Serpent River and Port Hope areas are not affecting the Lakes as a whole. Note that, if the ambient level of radium in Huron approached 1 pCi per liter, Lake Erie would not be relatively free of radium, since a major fraction of Lake Erie water is from Lake Huron.

[1]Concentrations are so low as to be below the quantitative analytical limit of most laboratories.

Table 5

Reported Radium-226 Concentrations in Ambient Waters of the Great Lakes

Lake	pCi/l	References and Remarks
Superior	---	no data
Michigan	0.03	11
Michigan	0.03	12
Huron	---	no data except Serpent River
Erie	<0.03	13 - Dunkirk (raw water)
Erie	0.03	14
Ontario	<0.03	15 - Oswego (finished water)

The dose due to the ingestion of radium-226 is still being considered by the ICRP Committee II. The new ICRP approach is based on Thorne's Monte Carlo calculations of the average alpha particle dose to tissue, 0-10 μ from endosteal surfaces and to marrow within the cavities of trabecular bone (6,18). Radium retention is based on the results provided in ICRP Report #20, (8) Although this metabolism model is not generally applicable to environmental sources of radium, the use of ICRP models for occupational exposures is required in the Draft Refined Objectives.

The TED(50) from the ingestion of 803 pCi of radium-226 in one year will be about 16 mrems to bone endosteum and 0.34 mrem to marrow, based on a quality factor of 20 for alpha particle irradiation (18,3), see also Appendix A. These dose estimates cannot be compared to limits in the Objective until weighted by appropriate ICRP estimates of the risk relative to total body irradiation. Taking these weights

into consideration, ingestion of water containing 1 pCi/l of radium-226 at the rate of 2.2 liters per day for a year would result in total body dose equivalent of about 0.5 mrem.

Assuming the ambient concentration of radium-226 in Lake Waters is something like 0.03 pCi/l, the TED outside of areas of contamination would not be expected to exceed 0.02 mrem. This is a factor of 50 less than Condition B and a factor of 500 less than Condition C.

Where radium contamination has resulted in concentrations as high as 5.3 pCi/l (mouth of the Serpent River) the TED(50) due to radium is estimated as about 3 mrem. This may exceed the Proposed Refined Objective and is one of the reasons Canadian officials are seeking to impose as low as readily achievable effluent limits on mine wastes entering this river. Adoption of the Proposed Refined Objective would provide an added incentive for this effort.

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Appendix A

ICRP Dosimetry for Internal Emitters

INTRODUCTION

For the last five years, ICRP Committee 2 has been working on a dosimetry system for internal emitters to replace the Committee II report of 1959. This system of dosimetry has been described in part in numerous annual reports from the Health Physics Division of the Oak Ridge National Laboratory and is similar to the system of internal dosimetry developed by the MIRD Committee of the Society of Nuclear Medicine. Unlike the 1959 ICRP system which is based on dose rates from long term ingestion or inhalation, the new system is used to calculate the dose commitment, over 50 years, from a single intake, i.e., rem per μCi intake.

In order that the Refined Objective would not become obsolete in terms of ICRP concepts and terminology, the new ICRP dosimetry and ICRP Reference Man (ICRP Report #23) have been used by the Working Group that drafted the Objective. This was done in anticipation that publication of ICRP #26 and a new ICRP Committee 2 Report would precede that of the Objective. Unfortunately, a delay in the publication of the Committee 2 Report upset this time-table. Therefore, some explanatory notes are given below to outline ICRP methodology for tritium, strontium-90, and radium-226.

1.1 ICRP terminology and definitions

H, the dose commitment to a given target organ, T, from radioactivity in the source organ, S, is given by

$$H = 51.2 \times U_s \times SEF(T \leftarrow S) \times Q \text{ rem.} \quad (1)$$

where U_s is the time integral of activity in μCi days accumulated in the source organ, S, and SEE is the specific effective energy absorbed (MeV) per gram in target organ per disintegration of activity in the source organ. For example, the SEE value utilized for bone seekers, such as strontium-90 and radium-226 is proportional to the energy absorbed by endosteal cells 0-10 μ from bone surfaces due to radioactivity in bone. For tritium, T and S are identical and the SEE is simply the emitted energy per gram - disintegration. The quality factor, Q, is assumed to be unity for beta particles and twenty for alpha particles, ICRP-26. ICRP retention functions for the Alkaline Earths are taken from ICRP #20; for tritium, from ICRP #23. When the period of integration used to evaluate U_s is 50 years, H is the TED(50) for the target organ.

2.1 Tritium - 50 year dose commitment per μCi

The source and target organs for tritium are those organs which contain body water. This mass is 42 kg and the concentration of water per gram is no greater than 80% (ICRP #23). The average beta particle energy from tritium is .0057 MeV.

$$SEE = \frac{.0057 \text{ MeV} \times .8}{42 \times 10^3} = 1.09\ 10^{-7} \frac{\text{MeV}}{\text{g dist.}} \quad (2)$$

$$T = 10 \text{ days}$$

$$U_s = \frac{10 \text{ days}}{\ln 2} = 14.4 \text{ days (for either 50 years or } \infty \text{ time)}$$

$$H \text{ (total body)} = 51.2 \times U_s \times SEE \times Q \quad (3)$$

$$= 51.2 \times 14.4 \times 1.09^{-7} \times 1 = 8 \times 10^{-5} \frac{\text{rem}}{\mu\text{Ci}}$$

2.2 Dose equivalent commitment for 1 pCi/l

An intake of 2.2 liter per day containing a concentration of 1 pCi/l corresponds to an annual intake for reference man of 803 pCi.

$$\text{Tritium} \quad \frac{\text{TED}(50)}{\text{pCi/l}} = 8.03 \times 10^{-4}\ \mu\text{Ci} \times 8 \times 10^{-5}\ \text{rem}/\mu\text{Ci} \qquad (4)$$

$$= 6 \times 10^{-5}\ \text{mrem.}$$

Since this is a total body dose, the ICRP risk weight is 1 and the weighted dose equivalent commitment = $w\,H = 1 \times 6 \times 10^{-5}$ $= 6 \times 10^{-5}$ mrem

3.1 Strontium-90 - 50 year dose commitment per μCi in blood

In the case of strontium-90 the source and target organs differ. Two source organs must be considered: cortical bone, c, and trabecular (cancellous) bone, t, and two target organs, endosteum cells and red marrow. ICRP SEE values are calculated by the method of Spiers. ICRP values for Sr-90 in bone provided by the Canadian Minister of Health are as follows:

For the endosteal cells, e

SEE (e ← c) = 2.5×10^{-5} $\frac{\text{MeV}}{\text{g dis}}$ Sr-90 parent Sr-90

SEE (e ← c) = 1.4×10^{-4} $\frac{\text{MeV}}{\text{g dis}}$ y-90 daughter Y-90

SEE (e ← t) = 4.6×10^{-5} $\frac{\text{Mev}}{\text{g dis}}$ Sr-90 parent Sr-90

SEE (e ← t) = 1.6×10^{-4} $\frac{\text{MeV}}{\text{g dis}}$ y-90 daughter Y-90

For red bone marrow, m

SEE (m ← c) = 6.17×10^{-7} $\frac{\text{MeV}}{\text{g dis}}$ Sr-90

SEE (m ← c) = 1.5×10^{-5} $\frac{\text{MeV}}{\text{g dis}}$ y-90

SEE (m ← t) = 4.5×10^{-5} $\frac{\text{MeV}}{\text{g dis}}$ Sr-90

SEE (m ← t) = 2.7×10^{-4} $\frac{\text{MeV}}{\text{g dis}}$ y-90

Fifty-year retention of Sr-90 in bone per μCi in blood including retention on bone surfaces ICRP 20 (Table 34 (b)).

U_c = 399 μCi day

U_t = 158 μCi day

TED(50) endosteum = $51.2 \times Q \; \Sigma \; U_s \times$ SEE (T ← S) (6)

Q = 1

TED(50) endosteum = $51.2 \times (399 \times 1.6 \times 10^{-4} + 158 \times 2.0 \times 10^{-4})$ (7)

= 4.9 rem per μCi

Marrow TED(50) = $51.2 \times (399 \times 1.6 \times 10^{-5} + 158 \times 3.2 \times 10^{-4})$ (8)

= 3 rem per μCi

3.2 Dose equivalent commitment for 1 pCi/l

Fraction of ingested strontium transferred to blood is 0.3. One year intake at 1 pCi/l and 2.2 liters per day = 803 pCi.

Endosteum TED(50) for 803 pCi intake

= 8.03×10^{-4} μCi x 0.3 x 4.9 $\frac{\text{rem}}{\mu\text{Ci}}$ = 1.2 mrem (9)

Marrow TED(50) for 803 pCi intake =

$8.03 \times 10^{-4} \times 0.3 \times 3.0$ rem/μCi = 0.7 mrem. (10)

Weighting these organ doses as prescribed in ICRP #26 yields the equivalent commitment $w_e H_e + w_m H_m$ =

0.03 x 1.2 mrem + 0.12 x .7 mrem = .12 mrem as the weighted (11)

dose equivalent commitment.

4.1 Radium - 50-year dose commitment per μCi in blood

The ICRP model for radium-226 is analogous to that for strontium-90 in that the dose commitment to endosteal cells and red marrow from radionuclides in bone is calculated. It differs from the calculation in ICRP Report #2 in other ways as well. Not only is the quality factor for alpha particles now 20, ICRP Report #26, but an increased retention of radon and radon decay products in bone is likely to be assumed also, so that the effective energy per disintegration is somewhat larger than in the older model.

Monte Carlo calculations of SEE values for compact and cancellous bone have been prepared for the ICRP by M. C. Thorne and are the basis for their refined model. His results (multiplied by the constant 51.2 in equation 1) have been published, as referenced in the text. For a radon retention of 0.3, the average dose to endosteal cells between 0 and 10 μ from bone surfaces is 0.05 rad per μCi day. Increased retention of radon decay products is not assumed in Thorne's published calculations, see below.

The retention of radium on cortical and cancellous bone and bone surface, integrated over 50 years, is 99.9 μCi days, ICRP #20. For Q = 20; H_e = 100 rem per μCi in blood.

$$\text{TED(50) endosteum} = \frac{0.05 \text{ rad}}{\mu\text{Ci day}} \times 99.9\ \mu\text{Ci day} \times \frac{20 \text{ rem}}{\text{rad}} = \frac{100 \text{ rem}}{\mu\text{Ci}} \quad (12)$$

For alpha emitters, only trabecular bone is assumed to irradiate red bone marrow. The 50-year retention of radium-226 on trabecular bone surfaces is 26 μCi days. Thorne's Table 2 lists 0.0040 rad per μCi day as the average dose to marrow for a radon retention of 0.3. For Q = 20; H_m =0.0040 x 26 x 20 = 2.1 rem/μCi in blood. (13)

4.2 Dose equivalent commitment for 1 pCi/l.

The fraction of ingested radium-226 transferred to blood is 0.2, ICRP Report #20. One year intake at 1 pCi/l and 2.2 liter per day = 803 pCi.

endosteum TED(50) for 803 pCi intake

$= 8.03 \times 10^{-4}\ \mu\text{Ci} \times 0.2 \times 100 \frac{\text{rem}}{} = 16 \text{ mrem}$ (14)

red marrow TED(50) for 803 pCi intake

$= 8.03 \times 10^{-4}\ \mu\text{Ci} \times 0.2 \times 2.1 \text{ rem}/\mu\text{Ci} = 0.34 \text{ mrem}$ (15)

Weighting these organ doses as prescribed in ICRP #26 yields

$(.03 \times 16 \text{ mrem}) + (.12 \times .34 \text{ mrem}) = .52 \text{ mrem}$ (16)

An increase in the assumed retention in bone of radon daughters would increase this value by a factor of about 1.4. The dose to other organs from radium-226 is very small. For example, the dose to gonads is about one-fifth that of marrow, UNSCEAR, Vol. I, Table 9, 1972.

Appendix B

Projected Concentrations of Radioactivity in the Lakes

This appendix summarizes the EPA studies, cited in the main text, of radionuclide concentrations in the Great Lakes due to future nuclear power operations. Although the original study included fuel reprocessing plants, this source of pollutants is not considered here since the operation of such facilities in the future is doubtful and the existing plant on Lake Erie is being decommissioned.

U.S. reactor discharges into the Great Lakes were quantified by calculating the number of one gigawatt(e) nuclear power plants needed to produce the electric power projected for the year 2000 and estimating the amount of activity in liquid form** released by each plant. The predominance of boiling water reactors on some of the Lakes now, is not likely to continue. Therefore, it was projected that by the year 2000 the ratio of pressurized water reactors (PWR) to boiling water reactors (BWR) on all of the Lakes would be 2 to 1. In projecting effluent releases, it was assumed that U.S. plants will conform to NRC design requirements by 1979. Tritium releases from PWRs are assumed to be 1200 curies (Ci) per gigawatt year; from BWRs 200 Ci. Prior to 1979, it was assumed that discharges of strontium-90 (Sr-90) per gigawatt year from PWR plants would be 4.4×10^{-2} Ci and after that date 2×10^{-3} Ci. For one gigawatt BWR plants the release

**Aerial releases are mainly noble gases and iodine. Compared to liquid releases, the amount of long half-life activity released into the air pathway is small.

of Sr-90 is assumed to be somewhat greater, 0.1 Ci/y before 1979 and 2.7×10^{-2} Ci/y thereafter. In spite of the smaller number of BWRs, their effluents determine the amount of Sr-90 entering the Lakes. The projected reduction of Sr-90 effluents after 1978 is not unduly optimistic. Recent final environmental statements (e.g., NRC-NUREG 0265) indicate design releases of 10^{-5} Ci per year.

The exact distribution between the various Lakes of sites for U.S. power plants in year 2000 is unknown. As a reasonable approximation, the number of plants on each Lake in the future was assumed to be in proportion to the total number of plants planned for each Lake in the 1980's, based on applications to the NRC for preliminary construction permits. Source terms for tritium in each of the Great Lakes, at five-year intervals, are listed in Table B-1. It is assumed that the source terms are constant after the year 2000, 193 gigawatt(e) installed capacity.

Table B-1

Projected Tritium Discharges into the Great Lakes
As a Function of Time - U.S. Power Reactors
(curies per year)

Period Ending	Michigan	Huron	Erie	Ontario
1970	----	----	----	3.6×10^2
1975	3.6×10^3	----	----	4.4×10^2
1980	3.7×10^3	1.9×10^2	8.8×10^2	5.5×10^2
1985	5.7×10^3	1.6×10^3	3.3×10^3	1.9×10^3
1990	1.0×10^4	3.1×10^3	6.6×10^3	3.7×10^3
1995	1.5×10^4	5.0×10^3	1.1×10^4	6.0×10^3
2000	2.2×10^4	7.3×10^3	1.6×10^4	8.8×10^3
2050	2.2×10^4	7.3×10^3	1.6×10^4	8.8×10^3

Table B-2 lists the projected concentration of tritium in each Lake at 10-year intervals through the year 2050. It is seen that an equilibrium tritium concentration is being approached after 50 years of constant effluent discharges, indicating that consideration of a long time period would not effect the TED(50) dose due to these sources.

Table B-2

Projected Concentration of Tritium in the Great Lakes
As a Function of Time Due to U.S. Power Reactors
(picocuries per liter)

Period Ending	Michigan	Huron	Erie	Ontario
1970	8.1×10^{-3}	1.4×10^{-3}	6.5×10^{-4}	1.8×10^{-1}
1980	3.7	5.9×10^{-1}	3.0	2.0
1990	1.1×10^{1}	5.8	2.7×10^{1}	1.6×10^{1}
2000	2.7×10^{1}	1.7×10^{1}	7.2×10^{1}	4.8×10^{1}
2010	3.9×10^{1}	2.8×10^{1}	8.9×10^{1}	7.2×10^{1}
2020	4.4×10^{1}	3.4×10^{1}	9.4×10^{1}	7.9×10^{1}
2030	4.6×10^{1}	3.6×10^{1}	9.6×10^{1}	8.1×10^{1}
2040	4.6×10^{1}	3.7×10^{1}	9.7×10^{1}	8.2×10^{1}
2050	4.6×10^{1}	3.8×10^{1}	9.7×10^{1}	8.2×10^{1}

The temporal pattern of strontium-90 discharges into the Lakes is quite similar to that for tritium, Table B-1, though, of course, at a much lower level. For example, in the year 2000 and thereafter; 0.38, 0.12, 0.28, and 0.19 curies of stroutium-90 are discharged into Michigan, Huror, Erie and Ontario respectively. The concentration of Sr-90 in the Lakes due to U.S. power reactors is shown in Table B-3 for projected discharges through the year 2050. As was the case for tritium, the Lakes are in a near equilibrium condition for Sr-90 by the year 2050.

Table B-3

Strontium-90 Concentrations in the Great Lakes
Due to Projected Releases from U.S. Reactors (pCi/l)

	Michigan	Huron	Erie	Ontario
1970	4.6×10^{-6}	8.1×10^{-7}	4.2×10^{-7}	1.7×10^{-5}
1980	7.2×10^{-5}	1.3×10^{-5}	2.7×10^{-4}	2.7×10^{-4}
1990	2.5×10^{-4}	1.2×10^{-4}	7.3×10^{-4}	6.8×10^{-4}
2000	6.0×10^{-4}	3.8×10^{-4}	1.6×10^{-3}	1.3×10^{-3}
2010	9.3×10^{-4}	6.9×10^{-4}	2.0×10^{-3}	1.9×10^{-3}
2020	1.1×10^{-3}	9.2×10^{-4}	2.2×10^{-3}	2.2×10^{-3}
2030	1.2×10^{-3}	1.1×10^{-3}	2.4×10^{-3}	2.4×10^{-3}
2040	1.3×10^{-3}	1.2×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
2050	1.3×10^{-3}	1.2×10^{-3}	2.6×10^{-3}	2.5×10^{-3}

Canadian releases of tritium into the Great Lakes as a function of time and the resulting concentrations are shown in Tables B-4 and B-5 respectively. As noted in the text the projected concentrations are based on an assumed 50 percent deposition of aerial releases into Lake waters. Canadian authorities believe the projected releases (based on current release rates) are apt to be high since the large economic incentive for deuterium oxide conservation will lead to improved containment in the future. Current Canadian plans indicate only Lakes Huron and Ontario will be the site of nuclear facilities.

Table B-4

Tritium Effluents from Canadian Reactors Assumed to Enter the Great Lakes (Curies)

Year	Huron	Ontario
1975	3.3×10^3	3.3×10^4
1980	5.3×10^4	4.2×10^4
1985	1.2×10^5	1.3×10^5
1990	2.4×10^5	1.7×10^5
1995	2.9×10^5	3.9×10^5
2000	3.9×10^5	4.6×10^5

Table B-5

Concentrations of Tritium Due to Releases From Canadian Reactors (pCi/l)

Year	Huron	Erie	Ontario
1980	6.0×10^1	2.9×10^1	1.0×10^2
1990	3.6×10^2	2.0×10^2	5.1×10^2
2000	7.2×10^2	4.6×10^2	1.5×10^2
2010	9.1×10^2	6.3×10^2	1.7×10^3
2020	9.7×10^2	6.8×10^2	1.8×10^3
2030	3.9×10^2	7.0×10^2	1.9×10^3
2040	1.0×10^3	7.1×10^2	1.9×10^1
2050	1.0×10^3	7.1×10^2	1.9×10^3

Analysis of Canadian liquid effluents indicate that the discharge of Sr-90 is very low, less than that of Co-60, and this source term has not been considered in the study. It should be noted, also, that

the Canadians do not reprocess nuclear fuels from commercial power reactors.

The data listed in Tables B-2, B-3, and B-5 and the dosimetric information in Appendix A were utilized to prepare Tables 3A and 3B in the main text.

ANNEX III

Great Lakes Computer Program

ANNEX III

Input to GLA-1 Program

Card 1

IVOL, IOPT, ISTP, IPRT, IDLP, ICON (6I5)

IVOL -1 = Read in 10 values of V(J).

The first 5 are used in the first half of DELT and the second 5 for the latter half.

0 = Use real lake volumes in first half of DELT and 17 meter depths in second half. These values are calculated internally.

+1 = Use the real volumes in both halves of DELT.

Also internally calculated.

IØPT -1 = Print out all calculated sources and concentrations.

0 = Do not print sources or concentrations

+1 = Print out only concentrations

ISTP -1 = Use the last source read in as the total source for that time period (NYLST to NYLST)

0 = Last source read in is added to previous sources - source is cumulative.

+1 = Same as -1.

IPRT -1 = Print out both sets of doses/dose rates.

0 = Print only doses/dose rates for ICRP 10 and 10A treatment.

+1 = Print only doses/dose rates based on ICRP 2.

IDLP -1 = Print out results every DELPth time interval.

0 = Print out results every year.

+1 = Print out results every 10th year.

Card 2

NYST, NYND, DELT, DELP (2I10, 2F10.4)

NYST = Starting year for complete calculation. First results are for NYST + DELT.

NYND = Last year of entire calculation.

DELT = Time increment for calculation, usually one year. Problem is done in steps of 1/2 DELT. First step uses first 5 V(J) and second step last 5 V(J).

DELP = Time interval at which to print out results. First printout will be for the year which is an integral multiple of DELP.

Card 3

Use only if IC∅N = 1, -1

C∅(L,I) [Ci/cm³] (5E12.5)

C∅(L,I) = Initial concentrations. Same order as card 6. Read in 25 values.

Card 4

Use only if IVØL = -1

V(J)[cm^3] (5E12.5)

V(J) = Lake volumes in order: Superior, Michigan, Huron, Erie, Ontario. Read in 2 sets (10 values) to be used as described under DELT.

Card 5

NYLST, ISRC, ISYS (3I10)

NYLST = Last year in which these sources are to be used. First time period is from NYST to NYLST.

ISRC -1 = Read in sources for each lake (see card 6).

0 = Read in number of nominal 1000 MWe plants of each (BWR, PWR) type on each lake.

+1 = Same as 0 but read in additional source terms (see card 7) for each lake.

ISYS = 1 Radwaste system indicator

= 2 based on EPA-520/9-73-003-C,

= 3 the number of plants (see card 7)

= 4 will be used to internally calculate source terms for each lake and isotope.

If ISYS<0, set previous Sources = 0.0 and use new source for next time period.

Card 6

Use only if ISRC = -1

R(L,I) [Ci/yr] (5E12.5)

R(L,I) = the source terms for each lake (in card 4 order). For each lake the isotopic (H^3, $C0^{60}$, Sr^{90}, Cs^{134}. Cs^{137}) concentrations (Ci/yr); one lake per card. Total number of source terms is 25.

Card 7

Use only if ISRC = 0, 1

NB(L), NP(L) (10F5.2)

NB(L), NP(L) = the number of 1000 MWe plants (BWR, PWR) on each lake (in card 4 order), e.g., BWR (Superior), PWR (Superior),... BWR (Ontario), PWR (Ontario).

Card 8

Use only if ISRC = 1

FRP (L,I) (5E12.5)

FRP (L,I) = Additional source terms (as on card 6) to be added to those specified on card 7.

Return to Card 5 to specify source terms for next time period. Repeat cards 5-8 until NYLST = NYND.

```
0001              DOUBLE PRECISION RT, EXPO, FAC1, T1, T2, T3, T4, T5
0002              DIMENSION    V(10),Q(5),HLF(5),NB(5),NP(5),SA(5)
0003              DIMENSION CONC(5,5),EXPO(5,5),RT(5,5),COEF(5,5),CO(5,5),R(5,5),
                 *                SYSB(4,5),SYSP(4,5),ERP(5,5),ADL(5,5),
                 *                                  FAC1(5,5),COSTO(5,5),CBAR(5,5),PO(5,5)
0004              DIMENSION  DOSRAT(150,5,5),DOSSUM(150,5,5)
0005              DIMENSION    TY(100),DOSCON(10),5,5),DOSEXP(100,5,5)
0006              COMMON     NITY,IPRT,IOPT,DELT,DELP,YEAR,ENYST,ENYND
0007              DATA         V/12.221E+18,4.871E+18,3.52E+18,0.458E+18,1.636E+18/
0008              DATA         Q/0.652E+17,1.582E+17,1.573E+17,1.752E+17,2.091E+17/
0009              DATA         HLF/12.26,5.24,28.8,2.1,30.0/
0010              DATA         CO/25*0.0/
0011              DATA         SA/8.237E+14,5.802E+14,4.148E+14,2.557E+14,1.368E+14/
0012              DATA         SYSB/1.0E+2,1.0E+2,1.0E+2,6.5E+1,2.4E+1,6.5E-2,
                 1                  1.4E-2,1.05E-3,4.25,5.0E-2,1.35E-2,1.05E-3,
                 2                  3.7E+1,1.0E-1,5.0E-2,1.65E-4,3.15E+1,8.0E-2,
                 3                  4.25E-2,1.4E-4/
0013              DATA         SYSP/5.0E+2,5.0E+2,3.8E+2,3.8E+2,1.25,4.55E-2,1.8E-2,
                 1                  9.0E-7,2.2E-2,1.0E-3,4.75E-6,3.1E-7,1.45E+2,2.3,
                 2                  6.0E-1,1.7E-4,1.35E+2,2.0,6.0E-1,1.55E-4/
0014              DATA         ADL/3.43E-3,3.75E-3,1.06E-2,4.51E-2,9.15E-3,
                 1                  0.0,0.0,0.0,0.0,0.0,
                 2                  0.0,0.0,0.0,0.0,0.0,
                 3                  0.286,0.333,0.333,0.400,0.333,
                 4                  0.286,0.333,0.333,0.400,0.333/
0015              DATA     DOSRAT,DOSSUM/7500*0.0/
0016              DATA         DOSCON,DOSEXP/5000*0.0/
0017              DATA         RO/25*0.0/
0018              REAL         NB,NP
0019              WRITE(6,1010)
0020           1010 FORMAT(1H1)
               C       IDLP =   PO INT     READ IN/EVERY YEAR/EVERY 10 YEARS
               C       DELP ALSO CONTROLS IOPT AND IPRT
0021              READ(5,1000) IVOL,IOPT,ISTP,IPRT,IDLP,ICON
0022           1000 FORMAT(6I5)
0023              IF(IOPT.NE.-1) GO TO 10
0024              WRITE(6,1100) IVOL,IOPT,ISTP,IPRT,IDLP,ICON
0025           1100 FORMAT(1H ,6X,4HIVOL,6X,4HIOPT,6X,4HISTP,6X,4HIPRT,6X,4HIDLP,6X,4H
                 1ICON//I9,5I10//)
0026              10 READ(5,2000) NYST,NYND,DELT,DELP
               C       (NYND - NYST)/DELT MUST BE AN INTEGRAL NUMBER.
0027           2000 FORMAT(2I10,2F10.4)
0028              ENYST = FLOAT(NYST)
0029              ENYND = FLOAT(NYND)
0030              IF(IDLP.EQ.0) DELP=1.0
0031              IF(IDLP.EQ.1) DELP=10.0
0032              IF(DELT.LE.0.0) DELT = 1.0
               C       ICON     READ INIT CONS/NO READ/READ INIT CONS
0033              IF(ICON.EQ.0) GO TO 13
0034              READ(5,2010) ((CO(L,I),I=1,5),L=1,5)
0035           2010 FORMAT(5E12.5)
0036              13 ITY = 0
0037              YDX = ENYST
0038              KE = IFIX((ENYND-ENYST)/DELT)
0039              DO 15 K = 1,KE
0040              YDX = YDX + DELT
0041              IF(AMOD(YDX,DELP).NE.0.0) GO TO 15
0042              ITY = ITY + 1
```

```
0043              TY(ITY) = YDX
0044            15 CONTINUE
0045               NITY = ITY
0046               IF (NITY.GT.100) GO TO 25
0047               WRITE(6,2020) NYST,NYND,DELT
0048            2020 FORMAT(32X,24HTHIS CALCULATION IS FROM,I5,3H TO,I5,19H USING INTER
                   1VALS OF,F6.2,7H YEARS.//)
0049               WRITE(6,2030) DELP
0050            2030 FORMAT(1HO,38X,25HRESULTS WILL BE PRINTED IN,F5.2,15H YEAR INTERVA
                   1LS.////)
0051               NYOLD = NYST
0052            C     IVOL  -I/O-     READ 10 VOLS/5 REAL VOL+5*17 METERS/10 REAL VOLS
0053               IF(IVOL)111,222,333
0054             111 READ(5,3000) (V(J),J=1,10)
0055            3000 FORMAT(5E12.5)
0056               GO TO 350
0057             222 DO 232 J=1,5
0058               V(J+5) = 1.E+30*A(J)
0059             232 CONTINUE
0060               GO TO 350
0061             333 DO 343 J=1,5
0062               V(J+5) = V(J)
0063             343 CONTINUE
0064             350 WRITE(6,3030)
0065            3030 FORMAT(16X,83HTHE VOLUMES USED FOR THE FIRST HALF OF THE TIME INTE
                   1RVAL ARE, IN CUBIC CENTIMETERS,///)
0066               WRITE(6,3040)
0067            3040 FORMAT(1H ,21X,8HSUPERIOR,12X,8HMICHIGAN,12X,5HHURON,15X,4HERIE,14
                   1X,7HONTARIO/)
0068               WRITE(6,3050) (V(J),J=1,5)
0069            3050 FORMAT(10X,1P5E20.4///)
0070               WRITE(6,3060)
0071            3060 FORMAT(14X,84HTHE VOLUMES USED FOR THE SECOND HALF OF THE TIME INT
                   1ERVAL ARE, IN CUBIC CENTIMETERS,///)
0072               WRITE(6,3040)
0073               WRITE(6,3050) (V(J+5),J=1,5)
0074            C     NOW DO SOURCE OPTIONS
0075            C     TO START EACH TIME PERIOD, READ IN CONTROLS AND SOURCE.
0076            C     MAY CHANGE SYSTEM RADWASTE EACH TIME PERIOD.
0077            C     CI/YR SOURCES ARE READ IN    FIRST LAKE, ALL ISOTOPES, ETC.
0078               ITI = 0
0079             444 CONTINUE
0080               READ (5,5000) NYLST,ISRC,ISYS
0081            5000 FORMAT(3I10)
0082            C     ISRC  -I/O+       READ SOURCES/READ NB NP/READ NB NP + FRP
0083            C     IF ISYS LT 0, SET ANY PREVIOUS SOURCE TO 0 AND USE NEW ONLY.
0084               IF (ISYS.GE.0) GO TO 553
0085               DO 513 L = 1,5
0086               DO 513 I = 1,5
0087               RP(L,I) = 0.0
0088             513 CONTINUE
0089             553 IF (ISRC) 555,555,555
0090             555 READ (5,6060) ((RP(L,I),I=1,5),L=1,5)
0091            6060 FORMAT(5E12.5)
0092               GO TO 300
0093             565 READ(5,5050) (NB(L),NP(L),L=1,5)
0094            5050 FORMAT(10F5.2)
0095               IF (ISRC.LE.0) GO TO 888
```

```
0089              READ(5,4000)((ERP(L,I),I=1,5),L=1,5)
0090           4000 FORMAT(5F12.5)
               C    ISTP       NEW IS TOTAL/CUMULATIVE SOURCES/NOW IS TOTAL
0091            888 DO 777 L=1,5
0092                DO 777 I=1,5
0093                R(L,I) = NB(L)*SYSB(ISYS,I)+NP(L)*SYSP(ISYS,I)
0094                IF (ISRC.LE.0) GO TO 777
0095                R(L,I) = R(L,I) + ERP(L,I)
0096            777 CONTINUE
0097            300 CONTINUE
0098                IF(ISTP)375,350,375
0099            360 DO 363 L = 1,5
0100                DO 363 I = 1,5
0101                R(L,I) = R(L,I) + RO(L,I)
0102            363 CONTINUE
0103            375 IF(IOPT.NE.-1) GO TO 20
               C    PRINT OUT SOURCE TERMS DEPENDING ON IOPT.
0104                WRITE(6,6065)
0105           6065 FORMAT(1H1)
0106                WRITE(6,6070) NYLST
0107           6070 FORMAT(1HO,14X,50HTHE SOURCE TERMS (CI/YR) THROUGH THE PERIOD ENDI
                    1NG,I5,5H ARE,//)
0108                WRITE(6,3040)
0109                WRITE(6,6080)
0110           6080 FORMAT(4X,7HISOTOPE/)
0111                DO 6090 I=1,5
0112                WRITE(6,6082) I,(R(L,I),L=1,5)
0113           6082 FORMAT(I8,2X,1P5E20.5/)
0114           6090 CONTINUE
               C    SAME SET OF R(L,I) IS USED THROUGH NYLST.
0115                WRITE(6,7003)
0116           7003 FORMAT(1H1)
               C    DELT IS FULL TIME INTERVAL, RUN IS IN ONE-HALF DELT STEPS.
0117              20 YEAR = FLOAT(NYOLD)
0118                 YINT = FLOAT(NYLST - NYOLD)
0119                 NINTS = IFIX(2.0*YINT/DELT)
0120                 IF(NINTS.LT.300) GO TO 35
0121              25 WRITE(6,6091)
0122                 GO TO 50
0123           6091 FORMAT(1HK,14X,7HNUMBER OF TIME INTERVALS REQUESTED EXCEEDS THE M
                    1AXIMUM (150) PERMITTED./)
               C    START TIME LOOP.
0124              35 DO 800 NTIM = 1,NINTS
0125                 IF(MOD(NTIM,2).EQ.0) ITI = ITI + 1
               C     NOW LAKE LOOP.
0126                 DO 700 L = 1,5
               C     NOW ISOTOPE LOOP
0127                 LVX = L
0128                 IF (MOD(NTIM,2).EQ.0) LVX = L + 5
0129                 DO 600 I = 1,5
               C     NOW THE EQUATIONS. HEAVISIDE PARTIAL FRACTION EXPANSION USED FOR
               C     INVERSE TRANSFORMS.  CHECKED WITH FALTUNG INTEGRAL.
0130                 RT(L,I)=(0.693/HLF(I))+(Q(L)/V(LVX))+(ADL(L,I))
0131                 COEF(L,I)=R(L,I)/V(LVX)
0132                 EXPO(L,I)=DEXP(-RT(L,I)*DELT/2.0)
0133                 FAC1(L,I)=1.0/RT(L,I)
               C     FIRST TERM.
0134                 T1 = FAC1(L,I)
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0135              T2 = -EXPO(L,I)*FAC1(L,I)
0136              T3 = EXPO(L,I)
0137              CONC(L,I) = COEF(L,I)*(T1 + T2) + CO(L,I)* T3
0138              IF (L.LE.2) GO TO 600
0139              MM = 1
0140              IF(L.GT.3) MM = L-1
0141              MMM = 2
0142              IF(L.GT.3) MMM = L-1
0143              DO 503 M=MM,MMM
0144              MVX = M
0145              IF(MOD(NTIM,2).EQ.0) MVX = M + 5
0146              T1 = FAC1(L,I)*FAC1(M,I)
0147              T2 = EXPO(M,I)/(-RT(M,I)+RT(L,I))
0148              T3 = EXPO(L,I)/(-RT(L,I)+RT(M,I))
0149              CONC(L,I)=CONC(L,I)+(Q(M)/V(LVX))*(R(M,I)/V(MVX)*(T1+T2/(-RT(M,I))
                 1+T3/(-RT(L,I)))+CO(M,I)*(T2+T3))
0150            503 CONTINUE
0151              IF(L.LE.3) GO TO 600
0152              NN = 1
0153              IF(L.GT.4) NN = L-2
0154              NNN = 2
0155              IF(L.GT.4) NNN = L-2
0156              DO 504 N=NN,NNN
0157              NVX = N
0158              IF(MOD(NTIM,2).EQ.0) NVX = N + 5
0159              T1 = FAC1(L,I)*FAC1(L-1,I)*FAC1(N,I)
0160              T2 = EXPO(N,I)/((-RT(N,I)+RT(L,I))*(-RT(N,I)+RT(L-1,I)))
0161              T3 = EXPO(L-1,I)/((-RT(L-1,I)+RT(N,I))*(-RT(L-1,I)+RT(L,I)))
0162              T4 = EXPO(L,I)/((-RT(L,I)+RT(N,I))*(-RT(L,I)+RT(L-1,I)))
0163              CONC(L,I)=CONC(L,I)+(Q(L-1)/V(LVX)*Q(N)/V(LVX-1))*(R(N,I)/V(NVX)*(
                 1T1+T2/(-RT(N,I))+T3/(-RT(L-1,I))+T4/(-RT(L,I)))+CO(N,I)*(T2+T3+T4)
                 2)
0164            504 CONTINUE
0165              IF(L.LE.4) GO TO 600
0166              DO 505 K=1,2
0167              KVX = K
0168              IF(MOD(NTIM,2).EQ.0) KVX = K + 5
0169              T1 = FAC1(L,I)*FAC1(L-1,I)*FAC1(L-2,I)*FAC1(K,I)
0170              T2 =EXPO(K,I)/((-RT(K,I)+RT(L-2,I))*(-RT(K,I)+RT(L-1,I))*(-RT(K,
                 1I)+RT(L,I)))
0171              T3 = EXPO(L-2,I)/((-RT(L-2,I)+RT(K,I))*(-RT(L-2,I)+RT(L-1,I))*
                 1(-RT(L-2,I)+RT(L,I)))
0172              T4 = EXPO(L-1,I)/((-RT(L-1,I)+RT(K,I))*(-RT(L-1,I)+RT(L-2,I))*
                 1(-RT(L-1,I)+RT(L,I)))
0173              T5 = EXPO(L,I)/((-RT(L,I)+RT(K,I))*(-RT(L,I)+RT(L-2,I))*(-RT(L,I)
                 1+RT(L-1,I)))
0174              CONC(L,I)=CONC(L,I)+(Q(L-1)/V(LVX)*Q(L-2)/V(LVX-1)*Q(K)/V(LVX-2))*
                 1(R(K,I)/V(KVX)*(T1+T2/(-RT(K,I))+T3/(-RT(L-2,I))+T4/(-RT(L-1,I))+T
                 25/(-RT(L,I)))+CO(K,I)*(T2+T3+T4+T5))
0175            505 CONTINUE
0176            600 CONTINUE
0177            700 CONTINUE
                C     NOW OUT OF L,I LOOPS.
0178              YEAR = YEAR + 0.5 * DELT
0179              IF(MOD(NTIM,2).EQ.0) GO TO 750
0180            710 DO 735 I=1,5
0181              DO 725 L=1,5
0182              COSTO(L,I)=CO(L,I)
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0183                  CO(L,I)=CONC(L,I)
0184                725 CONTINUE
0185                735 CONTINUE
0186                  GO TO 800
0187                750 CONTINUE
                C     FOR SECOND HALF OF INTERVAL ONLY.
0188                  DO 775 L=1,5
0189                  LVX = L+5
0190                  DO 775 I=1,5
                C     STUFF AT BOTTOM RADIO DECAY ONLY.
                C     CBAR IS AVERAGE FOR HALF INTERVAL PLUS AVERAGE FOR HALF INTERVAL.
                C     CBAR IS AVERAGE OF HALF-YEAR AVERAGES.
0191                  CBAR(L,I)=(COST2(L,I)+2.0*CO(L,I)+CONC(L,I))/4.0
                C     CO IS NEW AVERAGE FOR END OF INTERVAL
0192                  EXLX = (0.693/HLF(I)) + ADL(L,I)
0193                  CO(L,I)=(CO(L,I)*EXP(-(    EXLX    )*(DELT/2.0))*(V(L)-V(LVX))+
                     1CONC(L,I)*V(LVX))/V(L)
                C     CONC IS NOT USED AGAIN.  PUT CBAR IN PCI/L IN TO PRINT.
                C     DO NOT DESTROY CBAR.  IT IS USED IN ALL DOSE SUBROUTINES.
0194                  CONC(L,I)=1.0E+15*CBAR(L,I)
                C     IN OUTSIDE (L,I) LOOP.
0195                775 CONTINUE
                C     COMING TO END OF T LOOP.
0196                  IF(IPRT.EQ.0) GO TO 780
0197                  IF(AMOD(YEAR,DELP).NE.0.0) GO TO 790
0198                780 WRITE(6,7000) YEAR
0199               7000 FORMAT(1H-,32X,39HRESULTS BELOW ARE FOR THE PERIOD ENDING,F8.2//)
0200                  WRITE(6,7010)
0201               7010 FORMAT(1H ,14X,60HCONCENTRATIONS (PCI/L) BY LAKE AND ISOTOPE AT EN
                     1D OF PERIOD.//)
0202                  WRITE(6,3040)
0203                  WRITE(6,6080)
0204                  DO 7025 I=1,5
0205                  WRITE(6,6082) I,(CONC(L,I),L=1,5)
0206               7025 CONTINUE
0207                790 CONTINUE
0208                  IF(IPRT.EQ.0) GO TO 7013
0209                  CALL DOSDCF (IT1,CBAR,DOSBAT,DOSSUM)
0210                  IF(IPRT.EQ.1) GO TO 7015
0211               7013 CALL DOSEXP (TY,CBAR,DOSCON,DOSEXP)
0212               7015 CONTINUE
0213                800 CONTINUE
                C     NOW OUT OF TIME LOOP. PERIOD IS NYOLD TO NYLST.
0214                  IF(ISTP)840,810,840
0215                810 DO 820 L = 1,5
0216                  DO 820 I = 1,5
0217                  PO(L,I) = P(L,I)
0218                820 CONTINUE
0219                840 NYOLD = NYLST
0220                  IF(NYLST.LT.NYND) GO TO 444
0221                 50 CONTINUE
0222                  WRITE(6,9000)
0223               9000 FORMAT(1H-,51X,11HEND OF CASE)
0224                  CALL EXIT
0225                  END
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0001              SUBROUTINE DOSDCF(ITI,CBAR,DOSRAT,DOSSUM)
0002              DIMENSION  CBAR(5,5),DCFX(5)
0003              DIMENSION  DOSRAT(150,5,5),DOSSUM(150,5,5)
0004              COMMON     NITY,IPRT,IOPT,DELT,DELP,YEAR,ENYST,ENYND
0005              DATA         DCFX/1.1E-7,5.0E-6,2.0E-3,6.1E-5,3.3E-5/
                  C     CBAR IS CURRENT (END OF YEAR) AVERAGE OF HALF-DELT AVERAGES.
                  C     ITI IS CURRENT VALUE OF NUMBER OF YEARS PROCESSED.
0006              DO 735 I=1,5
0007              DO 725 L=1,5
                  C     PUT DOSE IN MCI/L * U REM.
0008              DOSRAT(ITI,L,I) = 1.0E+21*DCFX(I)*CBAR(L,I)
0009              DOSSUM(ITI+1,L,I)=DOSSUM(ITI,L,I) + DOSRAT(ITI,L,I)*DELT
0010            725 CONTINUE
0011            735 CONTINUE
                  C     HAVE DOSES BY L AND I.
0012              IF(YEAR.LT.ENYND) GO TO 9000
0013              ITIT = ITI +1
0014              WRITE(6,7450)
0015              WRITE(6,7501)
0016              WRITE(6,7515)
0017            7515 FORMAT(1HK,33X,58HTHE FOLLOWING SET IS BASED ON EPA DOSE CONVERSIO
                    1N FACTORS.///)
0018              WRITE(6,7503) ENYST,ENYND
0019              DO 7710 L = 1,5
0020              IF(L.EQ.1) WRITE(6,7520)
0021              IF(L.EQ.2) WRITE(6,7530)
0022              IF(L.EQ.3) WRITE(6,7540)
0023              IF(L.EQ.4) WRITE(6,7550)
0024              IF(L.EQ.5) WRITE(6,7560)
0025              YUK = ENYST
0026              WRITE(6,6570)
0027            6570 FORMAT(1H0,44X,42HDOSE RATE (MICROREM/YR) TO CRITICAL ORGAN./)
0028              WRITE(6,7580)
0029              DO 6650 ITI = 1,ITI
0030              YUK = YUK + DELT
0031              DOSWB = 0.0
0032              DOSBM = 0.0
0033              DO 6660 I = 1,5
0034              IF (I.NE.3) DOSWB = DOSWB + DOSRAT(ITI,L,I)
0035            6660 IF (I.EQ.3) DOSBM = DOSBM + DOSRAT(ITI,L,I)
0036              IF(AMOD(YUK,DELP).NE.0.0) GO TO 6663
0037              WRITE(6,7590) YUK,(DOSRAT(ITI,L,I),I=1,5),DOSWB,DOSBM
0038            6663 CONTINUE
0039            6650 CONTINUE
0040              YUK = ENYST
0041              WRITE(6,7570)
0042              WRITE (6,7580)
0043              DO 7650 IT2=2,ITIT
0044              YUK = YUK + DELT
0045              DOSWB = 0.0
0046              DOSBM = 0.0
0047              DO 7660 I = 1,5
0048              IF (I.NE.3) DOSWB = DOSWB + DOSSUM(IT2,L,I)
0049            7660 IF (I.EQ.3) DOSBM = DOSBM + DOSSUM(IT2,L,I)
0050              IF(AMOD(YUK,DELP).NE.0.0) GO TO 7663
0051              WRITE(6,7590) YUK,(DOSSUM(IT2,L,I),I=1,5),DOSWB,DOSBM
0052            7663 CONTINUE
0053            7650 CONTINUE
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0054          7710 CONTINUE
0055          7450 FORMAT(1H1)
0056          7501 FORMAT(1H-,20X,88HCUMULATIVE DOSE RATES AND DOSES FOR EACH LAKE AN
                 1D ISOTOPE ARE GIVEN ON SUCCEEDING PAGES.///)
0057          7503 FORMAT(1HK,34X,32HTHESE RESULTS COVER THE INTERVAL,F8.2,2H -,F8.2,
                 11H.///)
0058          7520 FORMAT(1H1,57X,17HFOR LAKE SUPERIOR/)
0059          7530 FORMAT(1H1,57X,17HFOR LAKE MICHIGAN/)
0060          7540 FORMAT(1H1,57X,14HFOR LAKE HURON/)
0061          7550 FORMAT(1H1,57X,13HFOR LAKE ERIE/)
0062          7560 FORMAT(1H1,57X,15HFOR LAKE ONTARIO/)
0063          7570 FORMAT(1HO,40X,34HDOSE (MICROREM) TO CRITICAL ORGAN./)
0064          7580 FORMAT(1HO,2X,6HPERIOD,8X,7HTRITIUM,9X,9HCOBALT-60,7X,12HSTRONTIUM
                 1-90,6X,10HCESIUM-134,7X,10HCESIUM-137,15X,9HSUMMATION/1H ,2X,6HEND
                 2ING,6X,12H(TOTAL BODY),5X,12H(TOTAL BODY),5X,13H(BONE MARROW),4X,1
                 32H(TOTAL BODY),5X,12H(TOTAL BODY),5X,12H(TOTAL BODY),6X,13H(BONE M
                 4ARROW))
0065          7590 FORMAT(1HO,F8.2,1X,1P7E17.5/)
0066          9000 RETURN
0067               END
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0001              SUBROUTINE DOSEDO (TY,CBAR,DOSCON,DOSEXP)
0002              DOUBLE PRECISION  EST,SND,COE,QLC,QUC,FRST,LAST
0003              DIMENSION  EW(5),EPS(5),COM(5),JNT(5),A(5,5),B(5,5)
0004              DIMENSION  TY(100),CBAR(5,5),DOSCON(100,5,5),DOSEXP(100,5,5)
0005              COMMON     NITY,IPRT,IPRT,DELT,DELP,YEAR,ENYST,ENYND
0006              DATA     EW/1.0,0.3,0.30,1.0,1.0/
0007              DATA     EPS/0.010,1.50,5.5,0.59,0.59/
0008              DATA     COM/4.3E+4,7.0E+4,7.0E+3,7.0E+4,7.0E+4/
0009              DATA     A/1.0,0.0,0.0,0.0,0.0,0.0,
                 1           0.54,0.32,0.086,0.054,0.0,
                 2          0.10,0.17,0.73,0.0,0.0,
                 3          0.15,0.85,0.0,0.0,0.0,
                 4          0.15,0.85,0.0,0.0,0.0/
0010              DATA     B/25.3533,0.0,0.0,0.0,0.0,
                 1          973.664,140.754,18.2121,1.87790,0.0,
                 2          5.77675,0.08734,84.3968,0.0,0.0,
                 3          253.448,2.53103,0.0,0.0,0.0,
                 4          253.141,2.22413,0.0,0.0,0.0/
0011              DATA     JNT/1,4,3,2,2/
                C      DO THIS FOR EACH TARGET YEAR (TY) ONLY.
0012              DO 900 ITY = 1,NITY
0013              IF(TY(ITY).LT.YEAR) GO TO 900
0014              DO 800 I = 1,5
0015              JEND = JNT(I)
0016              QLC = 0.0
0017              QUC = 0.0
0018              DOSCOE = 1.8700E+15*EPS(I)/COM(I)
0019              DO 600 J = 1,JEND
0020              COE = A(J,I)/B(J,I)
0021              EST = -B(J,I)*(TY(ITY) - YEAR)
0022              SND = -B(J,I)*(TY(ITY) - YEAR + DELT)
0023              FRST = 0.0D+0
0024              IF(EST.GT.-1.50D+2) FRST = DEXP(EST)
0025              LAST = 0.0D+0
0026              IF(SND.GT.-1.50D+2) LAST = DEXP(SND)
0027              QLC = QLC+COE*(FRST-LAST)
0028              QUC = QUC+COE*((DELT)+(1.0/B(J,I))*(LAST-FRST))
0029            600 CONTINUE
0030              DO 700 L =1,5
                C      INGESTED WATER BASED ON 2.2 L/D INCLUDES EW (INGEST TO ORGAN).
0031              CBARLI = 8.0355E+6 * EW(I) * CBAR(L,I)
0032              DOSCON(ITY,L,I) = DOSCON(ITY,L,I)+DOSCOE*CBARLI*QLC
0033              DOSEXP(ITY,L,I) = DOSEXP(ITY,L,I)+DOSCOE*CBARLI*QUC
0034            700 CONTINUE
0035            800 CONTINUE
0036            900 CONTINUE
0037              IF(YEAR.LT.ENYND) GO TO 9500
0038              WRITE(6,1000)
0039           1000 FORMAT(1H1)
0040              WRITE(6,2000)
0041           2000 FORMAT(1H-,44X,45HRESULTS BASED ON ICRP PUBLICATIONS 10 AND 10A//)
0042              WRITE(6,3000) ENYST,ENYND
0043           3000 FORMAT(1HK,41X,32HTHESE RESULTS COVER THE INTERVAL,F8.2,2H -,F8.2,
                 11H.///)
0044              DO 1111 L = 1,5
0045              WRITE(6,4000)
0046           4000 FORMAT(1H1)
0047              IF(L.EQ.1) WRITE (6,4001)
```

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0048              IF(L.EQ.2) WRITE (6,4002)
0049              IF(L.EQ.3) WRITE (6,4003)
0050              IF(L.EQ.4) WRITE (6,4004)
0051              IF(L.EQ.5) WRITE (6,4005)
0052         4001 FORMAT(1H1,57X,17HFOR LAKE SUPERIOR/)
0053         4002 FORMAT(1H1,57X,17HFOR LAKE MICHIGAN/)
0054         4003 FORMAT(1H1,57X,14HFOR LAKE HURON/)
0055         4004 FORMAT(1H1,57X,13HFOR LAKE ERIE/)
0056         4005 FORMAT(1H1,57X,16HFOR LAKE ONTARIO/)
0057              WRITE(6,5000)
0058         5000 FORMAT(1HO,44X,42HDOSE RATE (MICROREM/YR) TO CRITICAL ORGAN./)
0059              WRITE(6,6000)
0060         6000 FORMAT(1HO,19X,6HPERIOD,8X,7HTRITIUM,9X,9HCOBALT-60,7X,12HSTRONTIU
                 1M-90,6X,10HCESIUM-134,7X,10HCESIUM-137/14 ,19X,6HENDING,6X,12H(BOD
                 2Y WATER),5X,12H(TOTAL BODY),5X,13H   (BONE)    ,4X,12H(TOTAL BODY)
                 3,5X,12H(TOTAL BODY))
0061              DO 2222 ITY = 1,NITY
0062              WRITE(6,7000) TY(ITY),(DOSCON(ITY,L,I),I=1,5)
0063         7000 FORMAT(1HO,17X,F8.2,1X,1P5E17.5/)
0064         2222 CONTINUE
0065              WRITE(6,5500)
0066         5500 FORMAT(1HO,49X,34HDOSE (MICROREM) TO CRITICAL ORGAN./)
0067              WRITE(6,6600)
0068         6600 FORMAT(1HO,19X,6HPERIOD,9X,7HTRITIUM,9X,9HCOBALT-60,7X,12HSTRONTIU
                 1M-90,6X,10HCESIUM-134,7X,10HCESIUM-137/14 ,19X,6HENDING,6X,12H(BOD
                 2Y WATER),5X,12H(TOTAL BODY),5X,13H   (BONE)    ,4X,12H(TOTAL BODY)
                 3,5X,12H(TOTAL BODY))
0069              DO 3333 ITY = 1,NITY
0070              WRITE(6,7700) TY(ITY),(DOSEXP(ITY,L,I),I=1,5)
0071         7700 FORMAT(1HO,17X,F8.2,1X,1P5E17.5/)
0072         3333 CONTINUE
0073         1111 CONTINUE
0074         9500 RETURN
0075              END
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